METHOD FOR MAKING A MICROSTRUCTURE BY SURFACE MICROMACHINING

FIELD OF THE INVENTION

The present invention generally relates to making a microstructure by surface micromachining. One aspect relates to making a structurally reinforced microstructure to provide a flatter profile on one or more of its structural layers. Another aspect relates to providing a plurality of at least generally laterally extending etch release channels to facilitate the release of the microstructure from the substrate.

BACKGROUND OF THE INVENTION

There are a number of microfabrication technologies that have been utilized for making microstructures (e.g., micromechanical devices, microelectromechanical devices) by what may be characterized as micromachining, including LIGA (Lithographie, Galvonoformung, Abformung), SLIGA (sacrificial LIGA), bulk micromachining, surface micromachining, micro electrodischarge machining (EDM), laser micromachining, 3-D stereolithography, and other techniques. Bulk micromachining has been utilized for making relatively simple micromechanical structures. Bulk micromachining generally entails cutting or machining a bulk substrate using an appropriate etchant (e.g., using liquid crystal-plane selective etchants; using deep reactive ion etching techniques). Another micromachining technique that allows for the formation of significantly more complex microstructures is surface micromachining. Surface micromachining generally entails depositing alternate layers of structural material and sacrificial material using an appropriate substrate which functions as the foundation for the resulting microstructure. Various patterning operations may be executed on one or more of these layers

before the next layer is deposited so as to define the desired microstructure. After the microstructure has been defined in this general manner, the various sacrificial layers are removed by exposing the microstructure and the various sacrificial layers to one or more etchants. This is commonly called "releasing" the microstructure from the substrate, typically to allow at least some degree of relative movement between the microstructure and the substrate. Although the etchant may be biased to the sacrificial material, it may have some effect on the structural material over time as well. Therefore, it is generally desirable to reduce the time required to release the microstructure to reduce the potential for damage to its structure.

Microstructures are getting a significant amount of attention in the field of optical switches. Microstructure-based optical switches include one or more mirror microstructures. Access to the sacrificial material that underlies the support layer that defines a given mirror microstructure is commonly realized by forming a plurality of small etch release holes down through the entire thickness or vertical extent of the mirror microstructure (e.g., vertically extending/disposed etch release holes). The presence of these small holes on the upper surface of the mirror microstructure has an obvious detrimental effect on its optical performance capabilities. Another factor that may have an effect on the optical performance capabilities of such a mirror microstructure is its overall flatness, which may be related to the rigidity of the mirror microstructure. "Flatness" may be defined in relation to a radius of curvature of an upper surface of the mirror microstructure. This upper surface may be generally convex or generally concave. Known surface micromachined mirror microstructures have a radius of curvature of no more than about 0.65 meters.

BRIEF SUMMARY OF THE INVENTION

The present invention is generally embodied in a method for making a microstructure by surface micromachining. In this method, at least one and more typically a plurality of at least generally laterally extending etch release channels or conduits are formed within a sacrificial material. This sacrificial material is used to fabricate the microstructure on an appropriate substrate. At least some of this sacrificial material is removed when the microstructure is released from the substrate (and thereby encompassing the situation where all of this sacrificial material is removed).

A first aspect of the present invention is embodied in a method for making a microstructure by surface micromachining that includes forming a first structural layer over a sacrificial material. "Over" includes being deposited directly on the substrate or being deposited on an intermediate layer that is disposed between the subject sacrificial layer and the substrate. "On" in contrast means that there is an interfacing relation. In any case, a plurality of hollow etch release pipes, channels, conduits, or the like extend at least generally laterally through/within this sacrificial material. Lateral or the like, as used herein, means that the etch release conduits are disposed or oriented in a direction which is at least generally parallel with the substrate. Although the etch release conduits will typically extend laterally at a constant elevation relative to the substrate, such need not necessarily be the case. Ultimately, at least some of the sacrificial material is removed at least in part by allowing an etchant to flow through any and all of these hollow etch release conduits (and thereby encompassing the situation where all of this sacrificial layer is removed).

Various refinements exist of the features noted in relation to the first aspect of the present invention. Further features may also be incorporated in the first aspect of the present invention

as well. These refinements and additional features may exist individually or in any combination. In one embodiment, at least one end of at least one etch release conduit may be disposed at least generally at the same radial position as a perimeter of the first structural layer. Hereafter, "at least generally at the same radial position" in relation to any end of any etch release conduit or structure used to define the same means within 50 μm of the radial position of the perimeter of the relevant structural layer in one embodiment, more preferably within 25 μm of the radial position of the perimeter of the relevant structural layer in another embodiment, and even more preferably at the same radial position as the perimeter of the relevant structural layer. As such, the etchant does not have to etch in from the perimeter "too far" before encountering an open end of one or more etch release conduits associated with the first aspect. Reducing the time required for the etchant to reach the etch release conduits should at least to a point reduce the overall time for accomplishing the release of the microstructure from the substrate.

Various layouts of the plurality of etch release conduits in the noted lateral dimension may be utilized in relation to the first aspect. In one embodiment, each of the plurality of etch release conduits may be disposed in non-intersecting relation, in another embodiment the plurality of etch release conduits are disposed in at least substantially parallel relation, and in yet another embodiment at least some of the etch release conduits intersect. The plurality of etch release conduits may extend at least generally toward (and thereby including to) a common point, such as one that corresponds with a center of the first structural layer in the lateral dimension. All etch release conduits need not extend the same distance toward this common point, although such may be the case. Some of the plurality of etch release conduits may extend at least generally toward (and thereby including to) a first common point (e.g., one that corresponds with a center of the first structural layer in the lateral dimension), while some of the

plurality of etch release conduits may extend toward a different common point. The plurality of etch release conduits may also extend in the lateral dimension in a variety of configurations. In one embodiment, the plurality of etch release conduits are at least generally axially extending, while in another embodiment the plurality of etch release conduits are non-linear (e.g., in a sinusoidal configuration that is at least generally parallel with the substrate).

In one embodiment of the first aspect, the laterally extending etch release conduits are completely defined before the stack that includes the microstructure being fabricated by the methodology of the first aspect is exposed to a release etchant for removing the first sacrificial layer. One particularly desirable application for the first aspect is in the formation of a mirror microstructure or multiple mirror microstructures for a surface micromachined optical system that has at least some degree of movement relative to the first substrate. Because of the presence of the plurality of laterally extending etch release conduits, there is no need to have a plurality of etch release apertures or holes that extend entirely down through the entire vertical extent of the first structural layer to remove the sacrificial material that directly underlies this first structural layer. That is, there is no need for a plurality of vertically disposed etch release apertures, with "vertical" being at least generally opposite "lateral." As such, the upper surface of the first structural layer retains a very smooth surface that lacks any such vertically disposed etch release apertures, which makes the microstructure that is made by the methodology of the first aspect particularly suited for use in optical applications. This is true whether the upper surface of the first structural layer is the actual optical surface for the mirror microstructure, or whether a film or other layer is deposited on the first structural layer to provide more desirable optical properties/characteristics.

The sacrificial material that directly underlies the first structural layer used by the first aspect may actually be defined by the sequential deposition of multiple sacrificial layers, one on top of the other. That is, a lower portion of this sacrificial material may be formed as one layer, and an upper portion of this sacrificial material may be subsequently formed in overlying relation. Consider a case where a first sacrificial layer is formed over the first substrate, and where a first intermediate layer is formed on this first sacrificial layer. The first intermediate layer may be patterned to define a first subassembly (e.g., a plurality of strips). Portions of the first sacrificial layer are exposed by a patterning of the first intermediate layer to define the first subassembly. An upper portion of the first sacrificial layer (i.e., something less than the entirety of the first sacrificial layer) may be etched an amount after this patterning such that at least part of the first sacrificial layer that underlies at least part of the first subassembly is removed (e.g., using a timed etch). The first subassembly may be disposed directly on the first sacrificial layer, directly on a structural layer, or directly on both the first sacrificial layer and a structural layer (e.g., for the case where there is both a sacrificial material and a structural material at the same level within a stack which contains the microstructure being fabricated by the methodology of the subject first aspect).

The "gap" that now exists between the first subassembly and that portion of the etched first sacrificial layer that is directly beneath the first subassembly may be characterized as an undercut. A second sacrificial layer may be formed on at least the first sacrificial layer. One could characterize this as "backfilling." Notwithstanding this characterization of the backfilled sacrificial material as a "second sacrificial layer", the first and second sacrificial layers may in fact be indistinguishable from each other and may in effect define a continuous structure. Nonetheless, the sacrificial material that has been characterized as the second sacrificial layer

will not fill the entire extent of each of the undercuts. This failure to fill the undercuts defines the plurality of etch release conduits that are associated with the first aspect of the present invention. One could visualize that the first subassembly acts as an umbrella of sorts that prevents the material that has been characterized as the second sacrificial layer from totally filling the noted undercuts that are protected by the first subassembly. Typically the second sacrificial layer will also cover the first subassembly. In this case and possibly in other instances during the fabrication of the microstructure associated with the first aspect, it may be desirable to planarize an upper surface of a given layer before depositing the next layer thereon. One appropriate technique for providing this planarization function is chemical mechanical polishing.

The first subassembly may be a reinforcing structure for the first structural layer, in which case the first subassembly would exist in the microstructure that is defined by the methodology of the first aspect. Reinforcement may be provided by structurally interconnecting the first structural layer with the first subassembly through the above-noted second sacrificial layer which may be deposited on the first subassembly in addition to the first sacrificial layer as noted. Further reinforcement of the first structural layer may be accomplished by structurally interconnecting the first subassembly with a structural layer that underlies the first sacrificial layer. In both cases, the actual reinforcement structure could be in the form of a plurality of posts or columns that are disposed in spaced relation, in the form of a plurality of at least generally laterally extending ribs or rails, or in the form of a grid-like reinforcement structure.

The first subassembly need not remain in the microstructure that may be defined by the methodology of the first aspect. That is, the first subassembly need not be part of the final microstructure that is ultimately fabricated by the methodology of the first aspect. In this case, the only purpose of the first subassembly would be to at least assist in the formation of the

plurality of etch release conduits that are associated with the first aspect of the present invention. This "temporary" first subassembly may be in the form of a plurality of rails that are formed on or in a sacrificial material that is used in the methodology of the first aspect. Removal of the first subassembly from the final microstructure being made by the subject first aspect may be desirable in order to retain a low mass for this microstructure (e.g., in an upper structural layer of such a microstructure).

One way in which the first subassembly may be removed or alleviated from the final microstructure being made by the first aspect of the present invention is to form the first subassembly from a material that would be etched away along with the various sacrificial layers, although possibly at a different rate. Appropriate materials for the first subassembly in this case include silicon nitride, poly-silicon-germanium, or any other material that is soluble in the release etch or other etchant that will not have an adverse effect on any of the structural layers that may be included in the microstructure being made by the methodology of the subject first aspect. Having the first subassembly be of a reduced thickness may also contribute to the first subassembly being removed along with the sacrificial material within a desired time when releasing the microstructure made by the methodology of the first aspect. In one embodiment where the first subassembly is formed from silicon nitride and in the form of a plurality of strips, the first subassembly has a thickness or vertical extent of typically less than about 1,500 Å for this purpose.

Another option for creating the plurality of at least generally laterally extending etch release channels in accordance with the first aspect entails forming a first intermediate layer that will underlie the first sacrificial layer. This first intermediate layer may be patterned to define a plurality of at least generally laterally extending strips that are disposed in non-intersecting

relation over at least a portion of their length. These strips are spaced relatively close to each other such that when the first sacrificial layer is deposited on the first intermediate layer, the sacrificial material is unable to entirely fill the space between the adjacent strips. More specifically, an upper portion of the space between adjacent strips will "close off" during the deposition of the material that defines the first sacrificial layer before a lower portion of the space between the adjacent strips has had a chance to be filled with the material that defines the first sacrificial layer. Each "unfilled" void between adjacent pairs of strips defines one of the plurality of etch release channels referenced in relation to the first aspect. The manner in which the voids are formed may be characterized as "keyholing." Keyholing in relation to the first aspect is a result a relatively close spacing between adjacent strips in relation to their thickness or vertical extent. In one embodiment, a ratio of the height of these strips to the spacing between adjacent strips is at least about 1:1.

Further options exist for creating the plurality of at least generally laterally extending etch release channels in accordance with the first aspect. One way is to use multiple, different etchants. A first etchant that is not selective to the first sacrificial layer may be used to form the plurality of at least generally laterally extending etch release channels. A second, different etchant that is selective to the first sacrificial layer may thereafter be directed through the plurality of at least generally laterally extending etch release channels or conduits (again created/defined by the first etchant) to remove the first sacrificial layer. The first etchant may be selective to a material that forms a plurality of at least generally laterally extending etch release rails that are embedded or encased within the first sacrificial layer or at least in a sacrificial material. Any appropriate layout may be utilized for these plurality of at least generally laterally

extending etch release rails, including a plurality of separate and discrete etch release rails, a network or grid of interconnected etch release rails, or some combination thereof.

The intermediate structure in the fabrication of the microstructure in accordance with the first aspect may be characterized as a stack, and includes the various layers that are sequentially deposited on the substrate, and thereafter possibly patterned. This stack includes an exterior surface that is opposite the first substrate. Access to at least one of the etch release rails in the above-noted two etchant example may be provided by a first runner that extends from this exterior surface of the stack and at least generally toward the first substrate to a level such that it may structurally interconnect with at least one of the plurality of etch release rails. The same material that defines the etch release rails may define this first runner, such that the first etchant will first remove the first runner, and then each etch release rail that is structurally interconnected therewith (either directly or indirectly). Multiple first runners may be provided for accessing the plurality of etch release rails, multiple etch release rails may be accessed by a single first runner, or some combination thereof.

A second aspect of the present invention is embodied in a method for making a microstructure in which a plurality of at least generally laterally extending etch release channels or conduits are formed within a sacrificial material that is used to build/assemble the microstructure on an appropriate substrate, but which is at least in part removed when the microstructure is released from this substrate. These etch release channels do not exist until the release of the microstructure is initiated in the second aspect. In this regard, the method of the second aspect includes forming a first intermediate layer on top of a first sacrificial layer or possibly on top of the substrate. This first intermediate layer is patterned to define a plurality of at least generally laterally extending first strips that sit on top of the first sacrificial layer. A

second sacrificial layer is thereafter deposited on that portion of the first sacrificial layer which was exposed by the patterning of the first intermediate layer so as to be disposed at least alongside the first strips. Although not fundamentally required by the second aspect, the second sacrificial layer may also be disposed on top of the first strips as well. In any case, a first structural layer is formed on top of the second sacrificial layer. Both the first and second sacrificial layers are removed at least in part using an appropriate etchant. Generally, those portions of the second sacrificial layer that interface with or are disposed adjacent to the first strips etch at a greater rate than other portions of the second sacrificial layer which effectively defines a plurality of at least generally laterally extending etch release pipes, channels, conduits or the like. A plurality of hollow and at least generally laterally extending etch release channels or conduits (e.g., disposed at least generally parallel with an upper surface of the first substrate) are thereby formed in the second sacrificial layer by this differential etch rate. Although these etch release conduits will typically be disposed at a constant elevation relative to the substrate, such need not necessarily be the case. Ultimately, at least part of the second sacrificial layer, as well as the first sacrificial layer, are removed at least in part by allowing an etchant to flow through any and all of the noted conduits after the formation of the same in the releasing operation (and thereby encompassing the situation where all of the first and second sacrificial layers are removed, as well as the first intermediate layer if the same is not a structural material as discussed below).

Various refinements exist of the features noted in relation to the second aspect of the present invention. Further features may also be incorporated in the second aspect of the present invention as well. These refinements and additional features may exist individually or in any combination. The noted differential etch rate is believed to be based upon the density of that

portion of the second sacrificial layer in proximity to the first strips being less than a density of the remainder of the second sacrificial layer, as well as a density of the first sacrificial layer as well for that matter. The differential density is due to the sticking characteristics of the depositing atoms or molecules, which depends on the characteristics of the deposition technique. For example, the density of add-on molecules in a plasma-enhanced chemical vapor deposition (PECVD) system depends on directional orientation of the surface to the plasma body. In this way, atoms or molecules striking the surface have different energy available to them to aid in their positioning in low-energy (i.e. high-density) positions on the surface.

In one embodiment of the second aspect, at least one end of at least one first strip may be disposed at least generally at the same radial position as a perimeter of the first structural layer. Since the first strips effectively define the etch release conduits, at least one end of at least one etch release conduit may be disposed at this same radial position as well. As such, the etchant does not have to etch in from the perimeter "too far" before encountering a region that will have a higher etch rate, and that again defines a corresponding etch release conduit. The parameters mentioned above in relation to the first aspect regarding this feature are equally applicable to this second aspect.

Various layouts of the plurality of first strips (and thereby the etch release conduits) in the noted lateral dimension may be utilized in accordance with the second aspect. In one embodiment, each of the plurality of at least generally laterally first strips are further disposed in non-intersecting relation, in another embodiment each of the plurality of first strips are disposed in at least substantially parallel relation, and in yet another embodiment at least some of the first strips intersect. The plurality of first strips may extend at least generally toward (and thereby including to) a common point, such as one that corresponds with a center of the first structural

layer in the lateral dimension. All of the first strips need not extend the same distance toward this common point, although such may be the case. Some of the plurality of strips may extend at least generally toward (and thereby including to) a first common point (e.g., one that corresponds with a center of the first structural layer in the lateral dimension), while some of the plurality of first strips may extend toward a different common point. The plurality of first strips utilized by the second aspect may also extend in the lateral dimension in a variety of configurations. In one embodiment, the plurality of first strips are at least generally axially extending, while in another embodiment the plurality of first strips are non-linear (e.g., in a sinusoidal configuration within a plane that is parallel with the substrate).

One particularly desirable application for the second aspect is in the formation of a mirror microstructure or multiple mirror microstructures for a surface micromachined optical system that has at least some degree of movement relative to the first substrate. Because of the different etch rates that result from the way in which the microstructure is made by the methodology of the second aspect, there is no need to have a plurality of vertically disposed etch release apertures that extend down entirely through the second structural layer to release the mirror microstructure from the first substrate by the removal of the underlying first and second sacrificial layers. As such, the upper surface of the second structural layer retains a very smooth surface that lacks any such vertically disposed etch release apertures, which makes the microstructure that is made by the methodology of the second aspect particularly suited for use in optical applications. This is true whether the upper surface of the second structural layer is the actual optical surface for the mirror microstructure, or whether a film or other layer is deposited on the second structural layer to provide more desirable optical properties/characteristics.

Typically the second sacrificial layer will also cover the first strips (again, formed from the first intermediate layer) such that they are effectively embedded between the first and second sacrificial layers. In this case, it may be desirable to planarize an upper surface of the second sacrificial layer before depositing the first structural layer thereon. It may also be desirable to planarize an upper surface of other layers within the microstructure made in accordance with the methodology of the second aspect as well before depositing another layer thereon. One appropriate technique for executing this planarization function is chemical mechanical polishing.

The first strips may be a reinforcing structure for the first structural layer and would then exist in the microstructure that is made by the methodology of the second aspect. Reinforcement may be provided by structurally interconnecting the first structural layer with the first strips through the above-noted second sacrificial layer which may be deposited on the first strips in addition to the first sacrificial layer as noted. Further reinforcement of the first structural layer may be accomplished by structurally interconnecting the first strips with a structural layer that underlies the first sacrificial layer and thereby the first structural layer. In both cases, the actual reinforcing structure could be in the form of a plurality of posts or columns that are disposed in spaced relation, in the form of a plurality of at least generally laterally extending ribs or rails, or in the form of a grid-like reinforcement structure.

A third aspect of the present invention is embodied in a method for making a surface micromachined microstructure. A first sacrificial layer is formed over a first substrate in a manner so as to define a plurality of at least generally laterally extending low density regions therein. A first structural layer is thereafter formed over the first sacrificial layer. The release of the first structural layer from the first substrate is affected by removing the first sacrificial layer

with an appropriate etchant. The etching rate within the low density regions of the first sacrificial layer is greater than in other regions of the first sacrificial layer.

Various refinements exist of the features noted in relation to the third aspect of the present invention. Further features may also be incorporated in the third aspect of the present invention as well. These refinements and additional features may exist individually or in any combination. The higher etch rate in the low density regions of the first sacrificial layer may define a plurality of at least generally laterally extending etch release pipes, channels, conduits, or the like, which in turn should reduce the time required to completely release the microstructure from the first substrate. Although the low density regions will typically be disposed at a constant elevation relative to the substrate, such need not be the case.

In one embodiment of the third aspect, at least one end of at least one low density region may be disposed at least generally at the same radial position as a perimeter of the first structural layer. Since the low density regions effectively define the etch release conduits, at least one end of at least one etch release conduit may be disposed at this same radial position as well. As such, the etchant does not have to etch in from the perimeter "too far" before encountering a low density region for definition of an etch release conduit(s). The parameters mentioned above in relation to the first aspect regarding this feature are equally applicable to this third aspect.

Various layouts of the plurality of low density regions, and thereby the etch release conduits, in the noted lateral dimension may be utilized in accordance with the third aspect. In one embodiment, each of the plurality of at least generally laterally extending low density regions are disposed in non-intersecting relation, in another embodiment each of the plurality of low density regions are disposed in at least substantially parallel relation, and in yet another embodiment at least some of the low density regions intersect. The plurality of low density

regions may extend at least generally toward (and thereby including to) a common point, such as one that corresponds with a center of the first structural layer in the lateral dimension. All of the low density regions need not extend the same distance toward this common point, although such may be the case. Some of the plurality of low density regions may extend at least generally toward (and thereby including to) a first common point (e.g., one that corresponds with a center of the first structural layer in the lateral dimension), while some of the plurality of low density regions may extend toward a different common point. The plurality of low density regions utilized by the third aspect may also extend in the lateral dimension in a variety of configurations. In one embodiment, the plurality of low density regions are at least generally axially extending, while in another embodiment the plurality of low density regions are non-linear (e.g., in a sinusoidal configuration within a plane that is at least generally parallel with the substrate).

One way in which the low density regions associated with the third aspect may be formed is by forming a second sacrificial layer over the first substrate, and then patterning the same to define a plurality of at least generally laterally extending etch release conduit apertures. Each of these etch release conduit apertures is defined by first and second sidewalls that are disposed in spaced relation to each other. The first sacrificial layer is formed such that the material of the first sacrificial layer is deposited within these etch release conduit apertures. The first sacrificial layer may be deposited on the top of the second sacrificial layer as well. In any case, the low density regions associated with the third aspect will thereby exist along the first and second sidewalls of each of the etch release conduit apertures.

One advantage of the above-noted method for defining the low density regions in accordance with the third aspect, and thereby for defining a plurality of etch release channels, is

that a layout of the low density regions may define a network or grid-like structure or such that a plurality of these low density regions cross and/or are interconnected in some manner. For instance, the patterning of the second sacrificial layer could define a repeating pattern of interconnected "diamonds," a honeycomb or honeycomb-like structure, or the like. This ability to define a network could further enhance the distribution of the etchant during the release of the first structural layer from the first substrate. Another advantage of this particular method for defining the low density regions, and thereby for defining a plurality of etch release channels, is that the same does not require the use of any structural layer or material for the formation thereof. Therefore, this particular embodiment of the third aspect could be used to enhance the release of a simple, single structural layer in a microstructure.

The above-noted methodology for defining the low density regions in accordance with the third aspect may also be utilized where structural reinforcement of the first structural layer is desired. Structural reinforcement of the first structural layer may be realized by having an appropriate reinforcement structure cantilever downwardly from a lower surface of the first structural layer. Another way to structurally reinforce the first structural layer is to structurally interconnect the first structural layer with an underlying structural layer. The only limitation on the use of any such reinforcement structure is that it should not extend downwardly through any of the noted low density regions so as to cut off any etch release channels. This may be done in variety of manners. Consider the case where the second sacrificial layer is patterned in the form of a honeycomb. A plurality of columns or posts could extend downwardly from the first structural layer through the "closed cell" portions of the honeycomb without intersecting with any of the low density regions which define the profile of the honeycomb (in plan view).

Notwithstanding the advantages of the above-noted method for forming the low density regions in accordance with the third aspect, these low density regions may also be defined in the manner discussed above in relation to the second aspect. Therefore, those features discussed above in relation to the second aspect may be used in this third aspect as well.

A fourth aspect of the present invention is embodied in a method for making a surface micromachined microstructure. A first sacrificial layer is formed over a first substrate. A first structural layer is formed over the first sacrificial layer. The release of the first structural layer from the first substrate is affected by what may be characterized as a two step etch. In this regard, a first etchant may be used to form a plurality of at least generally laterally extending etch release channels or conduits within the first sacrificial layer or so as to otherwise be embedded within a sacrificial material. A second, different etchant that is selective to the first sacrificial layer may thereafter be directed through the plurality of at least generally laterally extending etch release channels (again created/defined by the first etchant) to remove the first sacrificial layer.

Various refinements exist of the features noted in relation to the fourth aspect of the present invention. Further features may also be incorporated in the fourth aspect of the present invention as well. These refinements and additional features may exist individually or in any combination. The first etchant may be selective to a material that forms a plurality of at least generally laterally extending etch release rails that are embedded or encased within the first sacrificial layer or at least in a sacrificial material. Any appropriate layout may be utilized for these plurality of at least generally laterally extending etch release rails, including a plurality of separate and discrete etch release rails, a network or grid of interconnected etch release rails, or some combination thereof.

The intermediate structure in the fabrication of the microstructure in accordance with the fourth aspect may be characterized as a stack, and includes the various layers that are sequentially deposited on the substrate, and thereafter possibly patterned. This stack includes an exterior surface that is opposite the first substrate. Access to at least one of the noted etch release rails may be provided by a first runner that extends from this exterior surface of the stack and at least generally toward the substrate to a level such that it may interconnect with at least one of the plurality of etch release rails. The same material that defines the etch release rails may define this first runner, such that the first etchant will first remove the first runner, and then each etch release rail interconnected therewith. Multiple first runners may be provided for accessing the plurality of etch release rails, multiple etch release rails may be accessed by a single first runner, or some combination thereof.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

Figure 1A is a plan view of one embodiment of surface micromachined optical system that includes a movable mirror microstructure.

Figure 1B is a plan view of another embodiment of a surface micromachined optical system that includes a movable mirror microstructure.

Figure 1C is a bottom view of the surface micromachined optical system of Figure 1B.

Figure 2A is a cross-sectional view of one embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 2B is a cross-sectional view of a portion of the mirror microstructure of Figure 2A with an optical coating thereon.

Figure 3 is a cross-sectional view of the mirror microstructure of Figure 2A along line 3-3.

Figure 4 is a cross-sectional view of another embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 5 is a cross-sectional view of another embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 6 is a cross-sectional view of the mirror microstructure of Figure 5 taken along line 6-6, as well as of the mirror microstructure of Figure 7 taken along line 6-6.

Figure 7 is a cross-sectional view of another embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 8 is a cross-sectional view of the mirror microstructure of Figure 7 taken along line 8-8.

Figure 9A is a cross-sectional view of another embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 9B is a cross-sectional view of the mirror microstructure of Figure 9A taken along line 9B-9B.

Figure 10A is a cross-sectional view of another embodiment of a mirror microstructure that may be used in a surface micromachined optical system.

Figure 10B is a cross-sectional view of the mirror microstructure of Figure 10A taken along line 10B-10B.

Figure 10-C is a cross-sectional view of the mirror microstructure of Figure 10A taken along line 10C/D-10C/D.

Figure 10D is a cross-sectional view of a variation of the mirror microstructure of Figure 10A taken along line 10C/D-10C/D.

Figure 11A is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figure 11B is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figure 11C is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figure 11D is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figure 11E is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figure 11F is a cross-sectional view of another embodiment of a rail layout for structural reinforcement and/or rapid etch release.

Figures 12A-M are sequential views of one embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figures 13A-M are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figures 14A-F are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figures 15A-G are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figures 16A-C are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figures 17A-G are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

Figure 18A is a top/plan view of one embodiment of an etch release conduit aperture grid that may be defined using the methodology of Figure 17A-G, and at a point in time in the process corresponding with Figure 17B and along line 18A-18A in Figure 17B.

Figure 18B is a cutaway view of the embodiment of Figure 18A, at a point in time in the process corresponding with Figure 17F and along line 18B-18B in Figure 17F.

Figures 19A-F are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system, and which uses the same technique for forming a plurality of etch release conduits as the method of Figures 17A-G.

Figures 20A-D are sequential views of another embodiment for making one embodiment of a microstructure for a surface micromachined system.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will now be described in relation to the accompanying drawings which at least assist in illustrating its various pertinent features. Surface micromachined microstructures and methods of making the same are the general focus of the present invention. Various surface micromachined microstructures and surface micromachining techniques are disclosed in U.S. Patent Nos. 5,783,340, issued July 21, 1998, and entitled "METHOD FOR PHOTOLITHOGRAPHIC DEFINITION OF RECESSED FEATURES ON A SEMICONDUCTOR WAFER UTILIZING AUTO-FOCUSING ALIGNMENT"; 5,798,283,

issued August 25, 1998, and entitled "METHOD FOR INTEGRATING MICROELECTROMECHANICAL DEVICES WITH ELECTRONIC CIRCUITRY; 5,804,084, issued September 8, 1998, and entitled "USE OF CHEMICAL MECHANICAL POLISHING IN MICROMACHINING"; 5,867,302, issued February 2, 1999, and entitled "BISTABLE MICROELECTROMECHANICAL ACTUATOR"; and 6,082,208, issued July 4, 2000, and entitled "METHOD FOR FABRICATING FIVE-LEVEL MICROELECTROMECHANICAL STRUCTURES AND MICROELECTROMECHANICAL TRANSMISSION FORMED, the entire disclosures of which are incorporated by reference in their entirety herein.

The term "sacrificial layer" as used herein means any layer or portion thereof of any surface micromachined microstructure that is used to fabricate the microstructure, but which does not exist in the final configuration. Exemplary materials for the sacrificial layers described herein include undoped silicon dioxide or ~~silicon~~ oxide, and doped silicon dioxide or silicon oxide ("doped" indicating that additional elemental materials are added to the film during or after deposition). The term "structural layer" as used herein means any other layer or portion thereof of a surface micromachined microstructure other than a sacrificial layer and a substrate on which the microstructure is being fabricated. Exemplary materials for the structural layers described herein include doped or undoped polysilicon and doped or undoped silicon. Exemplary materials for the substrates described herein include silicon. The various layers described herein may be formed/deposited by techniques such as chemical vapor deposition (CVD) and including low-pressure CVD (LPCVD), atmospheric-pressure CVD (APCVD), and plasma-enhanced CVD (PECVD), thermal oxidation processes, and physical vapor deposition (PVD) and including evaporative PVD and sputtering PVD, as examples.

In more general terms, surface micromachining can be done with any suitable system of a substrate, sacrificial film(s) or layer(s) and structural film(s) or layer(s). Many substrate materials may be used in surface micromachining operations, although the tendency is to use silicon wafers because of their ubiquitous presence and availability. The substrate is essentially a foundation on which the microstructures are fabricated. This foundation material must be stable to the processes that are being used to define the microstructure(s) and cannot adversely affect the processing of the sacrificial/structural films that are being used to define the microstructure(s). With regard to the sacrificial and structural films, the primary differentiating factor is a selectivity difference between the sacrificial and structural films to the desired/required release etchant(s). This selectivity ratio is preferably several hundred to one or much greater, with an infinite selectivity ratio being preferred. Examples of such a sacrificial film/structural film system include: various silicon oxides/various forms of silicon; poly germanium/poly germanium-silicon; various polymeric films/various metal films (e.g., photoresist/aluminum); various metals/various metals (e.g., aluminum/nickel); polysilicon/silicon carbide; silicone dioxide/polysilicon (i.e., using a different release etchant like potassium hydroxide, for example). Examples of release etchants for silicon dioxide and silicon oxide sacrificial materials are typically hydrofluoric (HF) acid based (e.g., undiluted or concentrated HF acid, which is actually 49 wt% HF acid and 51 wt% water; concentrated HF acid with water; buffered HF acid (HF acid and ammonium fluoride)).

Only those portions of a surface micromachined microstructure that are relevant to the present invention will be described herein. There may and typically will be other layers that are included in a given surface micromachined microstructure, as well as in any system that includes such microstructures. For instance and in the case where the surface micromachined

microstructures described herein are utilized as a movable mirror microstructure in a surface micromachined optical system, a dielectric isolation layer will typically be formed directly on an upper surface of the substrate on which such a surface micromachined optical system is to be fabricated, and a structural layer will be formed directly on an upper surface of the dielectric isolation layer. This particular structural layer is typically patterned and utilized for establishing various electrical interconnections for the surface micromachined optical system which is thereafter fabricated thereon.

One embodiment of at least a portion of a surface micromachined optical system 2 is presented in Figure 1A. The surface micromachined optical system 2 is fabricated on a substrate (not shown) and includes at least one microstructure in the form of a mirror microstructure 6. The surface micromachined optical system 2 may and typically will include multiple mirror microstructures 6 that are disposed/arranged in the form of an array (not shown), although there may be applications where only a single mirror microstructure 6 is required. The mirror microstructure 6 is interconnected with the substrate by a plurality of suspension springs 8. One end of each spring 8 is interconnected with the mirror microstructure 6, while its opposite end is interconnected with a structural support 4 that is in turn interconnected with the substrate (possibly through one or more underlying structural layers, which is the configuration shown in Figure 1A).

A lower electrode 10 is disposed below the mirror microstructure 6 in spaced relation and is interconnected with the substrate as well. An electrical contact 12a is interconnected with the lower electrode 10, while an electrical contact 12b is interconnected with the mirror microstructure 6. Appropriate voltages may be applied to both of the electrical contacts 12a, 12b to move the mirror microstructure 6 toward or away from the lower electrode 10 (and thereby the

substrate) into a desired position to provide an optical function. This movement is typically at least generally perpendicular relative to the lower electrode 10 and the substrate. The mirror microstructure 6 is commonly referred to as a piston mirror based upon the described motion.

Another embodiment of at least a portion of a surface micromachined optical system 16 is presented in Figures 1B-C. The surface micromachined optical system 16 is fabricated on a substrate (not shown) and includes at least one microstructure in the form of a mirror microstructure 20. The surface micromachined optical system 16 may and typically will include multiple mirror microstructures 20 that are disposed/arranged in the form of an array (not shown), although there may be applications where only a single mirror microstructure 20 is required. The mirror microstructure 20 is interconnected with the substrate by a pair of suspension springs 22. An imaginary line that extends between the springs 22 defines an axis about which the mirror microstructure 20 may pivot. One end of each spring 22 is interconnected with the mirror microstructure 20, while its opposite end is interconnected with a structural support 18 that is in turn interconnected with the substrate.

A pair of lower electrodes 24 are disposed below the mirror microstructure 20 and are interconnected with the substrate as well. One electrode 24a is associated with one side of the above-noted pivot axis, while the electrode 24b is associated with the opposite side of the above-noted pivot axis. There is one electrical contact 26a electrically interconnected with each lower electrode 24, while there is an electrical contact 26b electrically interconnected with the mirror microstructure 20. Appropriate voltages may be applied to appropriate ones of the contacts 26 to pivot the mirror microstructure 20 about its pivot axis in the desired direction and amount into a desired position to provide an optical function.

Details regarding a particular configuration of a mirror microstructure in a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, are presented in Figures 2A and 3 in the form of a two-layered mirror microstructure 30. The mirror microstructure 30 is made on an appropriate substrate 54 by surface micromachining techniques. Components of the mirror microstructure 30 include a first structural layer or support 34 that is spaced vertically upward relative to the substrate 54 (e.g., disposed at a higher elevation relative to the substrate 54), a second structural layer or support 38 that is spaced vertically upward relative to the first structural layer 34 (e.g., disposed at a higher elevation relative to the substrate 54), and a plurality of separate and discrete columns or posts 50 that are disposed in spaced relation. The columns 50 extend between and fixedly interconnect the first structural layer 34 and the second structural layer 38 for providing structural reinforcement for the microstructure 30 and, more particularly, the second structural layer 38. The columns 50 may be disposed in either equally spaced relation or the spacing between adjacent columns 50 may vary in at least some manner. Therefore, the second structural layer 38 and first structural layer 34, along with the interconnecting columns 50, may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

An upper surface 46 of the second structural layer 38 is or may include an optically reflective layer or film. That is, the materials that are used to define the second structural layer 38 may provide the desired/required optical properties/characteristics for the mirror microstructure 30. More typically a separate layer or film 48 (Figure 2B) will be deposited on an upper surface 46 of the second structural layer 38 to realize the desired/required optical properties/characteristics. Appropriate materials that may be deposited on the second structural

layer 38 for providing the desired/required optical properties include gold, silver, and aluminum for metal coatings. For metals, gold and an associated adhesion layer are preferable to obtain a suitable reflectance.

Depending upon the method of manufacture, a plurality of small etch release holes (not shown) may be formed through the entire vertical extent of the first and/or second structural layer 34, 38 to allow for the removal of any sacrificial layer(s) that is disposed between the first structural layer 34 and the second structural layer 38 of the mirror microstructure 30, and that is disposed between the first structural layer 34 and the substrate 54, respectively, when the mirror microstructure 30 is released from the substrate 54 (i.e., during the fabrication of the mirror microstructure 30). For instance, using the general principles of the manufacturing technique represented in Figures 12A-M to define the microstructure 30 would require such etch release holes. It should be appreciated that having etch release holes that extend entirely through the second structural layer 38, and which are thereby exposed on its upper surface 46, may have an adverse effect on its optical performance capabilities. Certain degradations in optical performance may be acceptable in some instances. However, the mirror microstructure 30 also may be made without having any etch release holes that extend down through the second structural layer 38, including in accordance with the methodology represented in Figure 17A-G.

Various desirable characteristics of the types of reinforced mirror microstructures described herein are addressed following the discussion of various other embodiments. Certain parameters are used in this summarization. One such parameter is the diameter of the uppermost structural layer in the mirror microstructure, and that is represented by the dimension "d_{SL}" ("SL" being an acronym for "structural layer"). "Diameter" does not of course limit this uppermost structural layer to having a circular configuration (in plan view), but is a simply the distance of a

straight cord or line that extends laterally from one location on a perimeter of this uppermost structural layer, through a center of this uppermost structural layer, and to another location on the perimeter of this uppermost structural layer. The dimension d_{SL} for the case of the mirror microstructure 30 thereby represents the diameter of the second structural layer 38 (the distance from one location on a perimeter 44 of the second structural layer 38, through a center 42 of the second structural layer 38, and to another location on this perimeter 44).

Another parameter that is used in the summarization of the desirable characteristics of the mirror microstructures disclosed herein is the distance from the center (in the lateral dimension) of the uppermost structural layer in the mirror microstructure to that reinforcing structure (by engaging a lower surface of this uppermost structural layer) which is closest to the center of this uppermost structural layer. This is represented by the dimension "d_{RS}" ("RS" being an acronym for "reinforcing structure"). The dimension d_{RS} for the case of the mirror microstructure 30 represents the distance from the center 42 of the second structural layer 38 to that column 50 which is closest to the center 42. A final parameter that is used in the noted summarization is the radius of curvature of the uppermost structural layer in the mirror microstructure (i.e., the amount which this uppermost structural layer is "cupped" or "bulged"). This is represented by the dimension RC. The dimension RC for the case of the mirror microstructure 30 thereby defines the radius of curvature of the second structural layer 38.

Another configuration of a mirror microstructure for a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, is presented in Figure 4 in the form of a three-layered mirror microstructure 58. The mirror microstructure 58 is fabricated on a substrate 60 by surface micromachining techniques. Components of the mirror microstructure

58 include a first structural layer or support 62 that is spaced vertically upward relative to the substrate 60 (e.g., disposed at a higher elevation than the substrate 60), a second structural layer or support 78 that is spaced vertically upward relative to the first structural layer 62 (e.g., disposed at a higher elevation relative to the substrate 60), a third structural layer or support 94 that is spaced vertically upward relative to the second structural layer 78 (e.g., disposed at a higher elevation relative to the substrate 60), a plurality of separate and discrete first columns or posts 74 that are disposed in spaced relation to each other, and a plurality of separate and discrete second columns or posts 90 that are also disposed in spaced relation to each other. The first columns 74 extend between and fixedly interconnect the first structural layer 62 and the second structural layer 78, while the second columns 90 extend between and fixedly interconnect the second structural layer 78 and the third structural layer 94, all for structurally reinforcing the mirror microstructure 58 and, more particularly, the third structural layer 94. Therefore, the first structural layer 62, the second structural layer 78, the interconnecting columns 74, the third structural layer 94, and the interconnecting columns 90 may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

The first columns 74 may be disposed in either equally spaced relation or the spacing between adjacent columns 74 may vary in at least some manner. The same applies to the columns 90. The plurality of first columns 74 may be offset in relation to the plurality of second columns 90 or such that no first column 74 is axially aligned (in the vertical direction) with any second column 90 as shown. However, other relative positionings between the plurality of first columns 74 and plurality of second columns 90 may be utilized as well, including where one or more of the plurality of first columns 74 is at least partially aligned with a second column 90.

An upper surface 102 of the third structural layer 94 is or includes an optically reflective layer or film. That is, the materials that are used to define the third structural layer 94 may provide the desired/required optical properties/characteristics for the mirror microstructure 58. More typically a separate layer or film will be deposited on the third structural layer 94 to realize the desired/required optical properties/characteristics. Those materials discussed above in relation to the mirror microstructure 30 for this purpose may be utilized by the mirror microstructure 58 and in the general manner illustrated in Figure 2B.

Depending upon the method of fabrication, a plurality of small release holes (not shown) may be formed through the entire vertical extent of one or more of the first structural layer 62, the second structural layer 78, and the third structural layer 94 to allow for the removal of any underlying and adjacently disposed sacrificial layer(s), or when the mirror microstructure 58 is released from the substrate 60 (i.e., during the fabrication of the mirror microstructure 58). For instance, using the general principles of the manufacturing technique represented in Figures 12A-M to define the mirror microstructure 58 would require such etch release holes. It should be appreciated that having etch release holes that extend entirely through the third structural layer 94, and which are thereby exposed on its upper surface 102, may have an effect on its optical performance capabilities. Certain degradations in optical performance may be acceptable in some instances. However, the mirror microstructure 58 also may be made without having any etch release holes that extend down through the third structural layer 94, including in accordance with the methodology represented in Figure 17A-G.

Certain parameters are identified on Figure 4 and that are addressed in the above-noted summarization of certain desirable characteristics that follows below. The dimension "d_{SL}" for the case of the mirror microstructure 58 represents the diameter of the third structural layer 94

(e.g., a line that extends laterally from one location on a perimeter 70 of the third structural layer 94, through a center 66 of the third structural layer 94, and to another location on this perimeter 70) that is being structurally reinforced collectively by the plurality of columns 90, the second structural layer 78, the plurality of columns 74, and the first structural layer 62. The dimension "d_{RS}" for the case of the mirror microstructure 58 represents the distance from the center 66 of the third structural layer 94 to that column 90 which is closest to the center 66. Finally, RC for the case of the mirror microstructure 58 represents the radius of curvature of the third structural layer 94.

Another configuration of a mirror microstructure for a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, is presented in Figures 5-6 in the form of a two-layered mirror microstructure 106. The mirror microstructure 106 is fabricated on a substrate 108 by surface micromachining techniques. Components of the mirror microstructure 106 include a first structural layer or support 110 that is spaced vertically upward relative to the substrate 108 (e.g., disposed at a higher elevation relative to the substrate 108), a second structural layer or support 122 that is spaced vertically upward relative to the first structural layer 110 (e.g., disposed at a higher elevation relative to the substrate 108), and a plurality of at least generally laterally extending ribs or rails 118 (i.e., with their length dimension being measured in a lateral dimension or at least generally parallel with the substrate 108). The upper and lower extremes of the rails 118 extend between and fixedly interconnect the first structural layer 110 and the second structural layer 122 to structurally reinforce the mirror microstructure 106 and, more particularly, the second structural layer 122. Therefore, the second structural layer 122 and

first structural layer 110, along with the interconnecting rails 118, may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

The rails 118 further extend at least generally laterally from one location on or at least generally proximate to a perimeter 116 of the microstructure 106 (e.g., within 50 μm of the perimeter 116, more preferably within 25 μm of this perimeter 116) to another location on or at least generally proximate to this perimeter 116 (e.g., within 50 μm of the perimeter 116, more preferably within 25 μm of this perimeter 116). In the illustrated embodiment, the rails 118 are of an axial or linear configuration in the lateral dimension, and further are disposed in at least generally parallel and equally spaced relation.

An upper surface 126 of the second structural layer 122 is or includes an optically reflective layer or film. That is, the materials that are used to define the second structural layer 126 may provide the desired/required optical properties/characteristics for the mirror microstructure 106. More typically a separate layer or film will be deposited on the second structural layer 122 to realize the desired/required optical properties/characteristics. Those materials discussed above in relation to the mirror microstructure 30 for this purpose may be utilized by the mirror microstructure 106 and in the general manner illustrated in Figure 2B.

There are a number of significant advantages in relation to the design utilized by the mirror microstructure 106 of Figures 5-6. First is in relation to its optical characteristics. The upper surface 126 of the second structural layer 122 of the mirror microstructure 106 need not and preferably does not include any vertically disposed etch release holes which extend downwardly therethrough in order to allow for the removal of any sacrificial material from between the first structural layer 110 and the second structural layer 122 when the microstructure 106 is released from the substrate 108, which significantly enhances the optical performance

capabilities of the mirror microstructure 106 (vertically disposed etch release holes would extend through the first structural layer 110 to remove any sacrificial material between the first structural layer 110 and the substrate 108). That is, preferably the upper surface 126 of the mirror microstructure 106 is continuous and devoid of any indentations, etch release holes, or the like (depressions or indentations that may develop on the upper surface 126 of the second structural layer 122 from the manufacture of the mirror microstructure 106 may be addressed by a planarization operation). Exactly how the mirror microstructure 106 may alleviate the need for the etch release holes in the second structural layer 122 will be discussed in more detail below in relation to the manufacturing methodologies represented in Figures 12A-M, 13A-M, 15A-G, and 17A-G. Suffice it to say for present purposes that the rails 118 may at least assist in the definition of a plurality of at least generally laterally extending etch release pipes, channels, or conduits in a sacrificial layer(s) that is disposed between the second structural layer 122 and the first structural layer 110 during the manufacture of the mirror microstructure 106. Any rails described herein that provide this function are characterized as etch release rails or the like. How the rails 118 are oriented relative to each other, or stated another way the layout of the rails 118, may have an effect on their ability to create this plurality of etch release channels or conduits within any sacrificial layer that is disposed between the first structural layer 110 and the second structural layer 122 during the manufacture of the mirror microstructure 106 by surface micromachining techniques. The general design considerations for etch release rails is summarized below following the description of other embodiments of microstructures that include etch release rails.

Another function provided by the plurality of rails 118 is structural reinforcement of the second structural layer 122. That is, the plurality of rails 118 structurally interconnect the second

structural layer 122 with the first structural layer 110. The structural reinforcement function of the rails 118 would not be adversely affected, and may in fact improve, by having at least some of the rails 118 be disposed in intersecting relation (e.g., see Figures 9A-B).

Certain parameters are identified on one or more of Figure 5-6 and that are addressed in the above-noted summarization of desirable characteristics that follows below. The dimension "d_{SL}" for the case of the mirror microstructure 106 represents the diameter of the second structural layer 122 (e.g., the distance of a line that extends from one location on the perimeter 116 of the second structural layer 122, through a center 114 of the second structural layer 122, and to another location on this perimeter) that is being structurally reinforced collectively by the plurality of rails 118 and the first structural layer 110. The dimension "d_{RS}" for the case of the mirror microstructure 106 represents the distance from the center 114 of the second structural layer 122 to that rail 118 that is closest to the center 114, which is "0" in the illustrated embodiment (Figure 6) since one of the rails 118 actually extends through the center 114. It should be appreciated that a rail 118 need not extend through the center 114, in which case d_{RS} would have a value greater than "0." Finally, RC for the case of the mirror microstructure 106 represents the radius of curvature of the second structural layer 122.

Another configuration of a mirror microstructure for a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, is presented in Figures 6-8 in the form of a three-layered mirror microstructure 130. The mirror microstructure 130 is fabricated on an appropriate substrate 132 by surface micromachining techniques. Components of the mirror microstructure 130 include a first structural layer or support 134 that is spaced vertically upward relative to the substrate 132 (e.g., disposed at a higher elevation than the substrate 132), a second

structural layer or support 146 that is spaced vertically upward relative to the first structural layer 134 (e.g., disposed at a higher elevation relative to the substrate 132), a third structural layer or support 158 that is spaced vertically upward relative to the second structural layer 146 (e.g., disposed at a higher elevation relative to the substrate 132), a plurality of at least generally laterally extending first rails 142, and a plurality of at least generally laterally extending second rails 154. The first rails 142 extend between and fixedly interconnect the first structural layer 134 and the second structural layer 146, while the second rails 154 extend between and fixedly interconnect the second structural layer 146 and the third structural layer 158, all to structurally reinforce the mirror microstructure 130 and, more particularly, the third structural layer 158. Therefore, the first structural layer 134, the second structural layer 146, the interconnecting rails 142, the third structural layer 158, and the interconnecting rails 154 may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

The rails 154 extend at least generally laterally from one location on or at least generally proximate to a perimeter 138 of the third structural layer 158 (e.g., within 50 μm of the perimeter 138, more preferably within 25 μm of this perimeter 138) to another location on or least generally proximate to this perimeter 138 (e.g., within 50 μm of the perimeter 138, more preferably within 25 μm of this perimeter 138). In the illustrated embodiment, the plurality of rails 154 are of an axial or linear configuration in the lateral dimension, and further are disposed in at least generally parallel and equally spaced relation. The plurality of rails 142 are also of an axial or linear configuration in the lateral dimension, and further are disposed in at least generally parallel and equally spaced relation.

An upper surface 162 of the third structural layer 158 is or includes an optically reflective layer or film. That is, the materials that are used to define the third structural layer 158 may provide the desired/required optical properties/characteristics for the mirror microstructure 130. More typically a separate layer or film will be deposited on the third structural layer 158 to realize the desired/required optical properties/characteristics. Those materials discussed above in relation to the mirror microstructure 30 for this purpose may be utilized by the mirror microstructure 130 and in the general manner illustrated in Figure 2B.

There are a number of significant advantages in relation to the design utilized by the mirror microstructure 130. First is in relation to its optical characteristics. The upper surface 162 of the third support layer 158 of the mirror microstructure 130 need not and preferably does not include any vertically disposed etch release holes in order to allow for the removal of any sacrificial material from between the third structural layer 158 and the second structural layer 146 when the microstructure 130 is released from the substrate 132, which significantly enhances the optical capabilities of the mirror microstructure 130. That is, preferably the upper surface 162 of the mirror microstructure 130 is continuous and devoid of any indentations, holes, or the like (depressions or indentations that may develop on the upper surface 162 of the third support layer 158 during the manufacture the microstructure 130 may be addressed by a planarization operation). Exactly how the mirror microstructure 130 may alleviate the need for any vertically disposed etch release holes in the third structural layer 158 will be discussed in more detail below in relation to the manufacturing methodologies represented in Figures 12A-M, 13A-M, 15A-G, and 17A-G. Suffice it to say for present purposes that the rails 154 may at least assist in the definition of a plurality of laterally extending etch release pipes, channels, or conduits in a sacrificial layer(s) that is disposed between the second structural layer 146 and the third

structural layer 158 during the manufacture of the mirror microstructure 130. As such, the rails 154 may be characterized as etch release rails as noted above. Again and in this case, how the rails 154 are oriented relative to each other, or stated another way the layout of the rails 154, may have an effect on their ability to create this plurality of etch release channels or conduits within any sacrificial layer that is disposed between the second structural layer 146 and the third structural layer 158 during the manufacture of the mirror microstructure 130 by surface micromachining techniques. The general design considerations for etch release rails again are summarized below following the description of the various embodiments of microstructures that include such etch release rails.

In the event that it would be desirable to avoid the use of etch release holes in the second structural layer 146 to allow for the removal of any sacrificial layer(s) that is disposed between the second structural layer 146 and the first structural layer 134, the characteristics noted above in relation to the rails 154 could be utilized by the rails 142 as well. Etch release holes would likely be required in the first structural layer 134 in order to allow for the removal of any sacrificial layer(s) that is disposed between the first structural layer 134 and the substrate 132 during the release of the microstructure 130 from the substrate 132.

Another function provided by the plurality of first rails 142 and second rails 154 is structural reinforcement of the mirror microstructure 130, and more particularly the third structural layer 158. It is believed that enhanced structural reinforcement is realized by having the plurality of first rails 142 disposed in a different orientation within the lateral dimension than the plurality of second rails 154. In the illustrated embodiment, the plurality of first rails 142 are disposed at least substantially perpendicular to the plurality of second rails 154 in the lateral dimension. The structural reinforcement function of the rails 142 and 154 would not be

adversely affected, and may fact improve, by having at least some of the rails 142 be disposed in intersecting in relation and/or by having at least some of the rails 154 be disposed in intersecting relation (e.g., see Figures 9A-B).

Certain parameters are identified on one or more of Figure 6-8 in relation to the mirror microstructure 130 and that are addressed in the above-noted summarization of desirable characteristics that follows below. The dimension "d_{SL}" for the case of the microstructure 130 represents the diameter of the third structural layer 158 (e.g., the distance of a straight line that extends from one location on the perimeter 138 of the third structural layer 158, through a center 136 of the third structural layer 158, and to another location on this perimeter 138) that is being structurally reinforced collectively by the plurality of rails 154, the second structural layer 146, the plurality of rails 142, and the first structural layer 134. The dimension "d_{RS}" for the case of the microstructure 130 represents the distance from the center 136 of the third structural layer 158 to that rail 154 that is closest to the center 136, which is "0" in the illustrated embodiment since one of the rails 154 actually extends through the center 136. It should be appreciated that a rail 154 need not extend through the center 136, in which case d_{RS} would have a value greater than "0." Finally, RC for the case of the mirror microstructure 130 represents the radius of curvature of the third structural layer 158.

Another configuration of a mirror microstructure for a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, is presented in Figures 9A-B in the form of a two-layered mirror microstructure 166. The mirror microstructure 166 is fabricated on a substrate 168 by surface micromachining techniques. Components of the mirror microstructure 166 include a first structural layer or support 170 that is spaced vertically upward relative to the

substrate 168 (e.g., disposed at a higher elevation relative to the substrate 168), a second structural layer or support 172 that is spaced vertically upward relative to the first structural layer 170 (e.g., disposed at a higher elevation relative to the substrate 168), a plurality of at least generally laterally extending first rails 174 that are disposed in spaced relation, and a plurality of at least generally laterally extending second rails 178 that are also disposed in spaced relation. Both the first rails 174 and the second rails 178 extend between and fixedly interconnect the first structural layer 170 and the second structural layer 172 to structurally reinforce the microstructure 166 and, more particularly, the second structural layer 172. In the illustrated embodiment, the plurality of first rails 174 are disposed in at least substantially parallel and equally spaced relation, as are the plurality of second rails 178. However, the plurality of first rails 174 are not disposed in the same orientation as the plurality of second rails 178 in the lateral dimension. In the illustrated embodiment, the first rails 174 are disposed at least substantially perpendicular to the second rails 178. As such, the first structural layer 170 and second structural layer 172, as well as the interconnecting rails 174, 178, may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

The plurality of first rails 174 and the plurality of second rails 178 will not form the type of etch release channels or conduits in any sacrificial layer that may exist between the first structural layer 170 and the second structural layer 172 during the manufacture of the mirror microstructure 166 using surface micromachining in comparison to the mirror microstructures 106 and 130 discussed above. As such, a plurality of small vertically disposed etch release holes (not shown) will typically extend through the entire vertical extent of the second structural layer 172 to allow for the removal of any sacrificial layer(s) that is disposed between the first structural layer 170 and the second structural layer 172 of the mirror microstructure 166 used in

the assembly thereof (a plurality of small vertically disposed etch release holes (not shown) will also typically extend through the entire vertical extent of the first structural layer 170 to allow for the removal of any sacrificial layer(s) that is disposed between the first structural layer 170 and the substrate 168 of the mirror microstructure 166 to release the microstructure 166 from the substrate 168). This again may have an adverse impact on the optical performance capabilities of an upper surface 176 of the second structural layer 172. However, the microstructure 166 still has desirable structural reinforcement characteristics. In this regard, the plurality of first rails 174 and the plurality of second rails 178 may be viewed as defining a grid 177 having a plurality of closed cells 179 (i.e., having a closed boundary). Any appropriate configuration may be used to define the perimeter of these closed cells 179 (e.g., a honeycomb, cylindrical), and each such closed cell 179 need not be of the same configuration.

An upper surface 176 of the second structural layer 172 is or includes an optically reflective layer or film of the type discussed above in relation to the mirror microstructure 30. Due to the likely existence of the plurality of vertically disposed etch release holes in the second structural layer 172, the upper surface 176 will at least have a plurality of dimples or the like which may have an effect on its optical performance capabilities. As such, the principal advantage of the mirror microstructure 166 is the structural reinforcement of the second structural layer 172 that is provided by the plurality of rails 174, 178 that structurally interconnect the second structural layer 172 with the first structural layer 170.

Certain parameters are identified on one or more of Figures 9A-B and that are addressed in the above-noted summarization of desirable characteristics that follows below. The dimension "d_{SL}" for the case of the microstructure 166 represents the diameter of the second structural layer 172 (e.g., the distance of a straight line that extends from one location on a perimeter 173 of the

second structural layer 172, through a center 171 of the second structural layer 172, and to another location on this perimeter 173) that is being structurally reinforced collectively by the plurality of rails 174, the rails, 178, and the first structural layer 170. The dimension "d_{RS}" for the case of the microstructure 166 represents the distance from the center 171 of the second structural layer 172 to that portion of the grid 177 that is closest to the center 171. Finally, RC for the case of the microstructure 166 represents the radius of curvature of the second structural layer 172.

Another configuration of a mirror microstructure for a surface micromachined optical system, such as for the mirror microstructures 6 and 20 in the surface micromachined optical systems 2 and 16 of Figures 1A and 1B-C, respectively, is presented in Figures 10A-C in the form of a reinforced, single-layer mirror microstructure 384. The mirror microstructure 384 is fabricated on a substrate 386 by surface micromachining techniques and is separated therefrom by a space 392. Other structural components could be disposed within this space 392, although any such structures would typically be spaced from the mirror microstructure 384 at least when providing its optical function. Components of the mirror microstructure 384 include a structural layer or support 404 that is spaced vertically upward relative to the substrate 386 (e.g., disposed at a higher elevation relative to the substrate 386); a plurality of at least generally laterally extending rails 400 that are fixedly interconnected with the structural layer 404, that extend toward but not to the substrate 386, and that are disposed in a first orientation; and a plurality of at least generally laterally extending rails 396 that are fixedly interconnected with the lower extreme of the rails 400 at a plurality of discrete locations, that extend toward but not to the substrate 386, and that are disposed in a second orientation that is different than the first orientation. In the illustrated embodiment, the rails 400 are disposed at least generally

perpendicular to the rails 396, although other relative orientations or relative angular positions could be utilized. Therefore, the structural layer 404, as well as the rails 400 and 396, may be moved simultaneously if acted upon by any interconnected actuator to provide a desired/required optical function.

At least the rails 400, and possibly the rails 396, extend at least generally laterally from one radial location corresponding with or at least generally proximate to a perimeter 390 of the microstructure 384 (e.g., within 50 μm of the perimeter 390, more preferably within 25 μm of this perimeter 390) to another radial location corresponding with or at least generally proximate to this perimeter 390 (e.g., within 50 μm of the perimeter 390, more preferably within 25 μm of this perimeter 390). In the illustrated embodiment, the rails 400 are of an axial or linear configuration in the lateral dimension, and are further disposed in at least generally parallel and equally spaced relation, while the rails 396 are also of an axial or linear configuration in the lateral dimension, and are further disposed in at least generally parallel and equally spaced relation.

An upper surface 406 of the structural layer 404 is or includes an optically reflective layer or film. That is, the materials that are used to define the structural layer 404 may provide the desired/required optical properties/characteristics for the mirror microstructure 384. More typically a separate layer or film will be deposited on the structural layer 404 to realize the desired/required optical properties/characteristics. Those materials discussed above in relation to the mirror microstructure 30 for this purpose may be utilized by the mirror microstructure 384 and in the general manner illustrated in Figure 2B.

There are a number of significant advantages in relation to the design utilized by the mirror microstructure 384. First is in relation to its optical characteristics. The upper surface

406 of the support layer 404 of the mirror microstructure 384 need not and preferably does not include any vertically disposed etch release holes which extend entirely through the structural layer 404 in order to allow for the removal of any sacrificial material from between the structural layer 404 and the substrate 386 when the microstructure 384 is released from the substrate 386, which significantly enhances the optical performance capabilities of the mirror microstructure 384. That is, preferably the upper surface 406 of the mirror microstructure 384 is continuous and devoid of any indentations, etch release holes, or the like (depressions or indentations that may develop on the upper surface 406 of the structural layer 404 from the manufacture of the mirror microstructure 384 may be addressed by a planarization operation). Exactly how the mirror microstructure 384 may alleviate the need for the etch release holes in the structural layer 404 will be discussed in more detail below in relation to the manufacturing methodologies represented in Figures 12A-M, 13A-M, 15A-G, and 17A-G. Suffice it to say for present purposes that the rails 396, the rails 400, or both may at least assist in the definition of a plurality of at least generally extending etch release pipes, channels, or conduits in a sacrificial layer(s) to allow for a more expedient removal of the same and without the need for any conventional etch release holes that extend downwardly entirely through the structural layer 404. As such, the plurality of rails 396 and 404 may both be characterized as etch release rails as noted above. Again and in this case, how the rails 400 are oriented relative to each other and how the rails 396 are oriented relative to each other, or stated another way the layout of the rails 396 and 404, may have an effect on their respective abilities to these etch release conduits within any sacrificial layer that is disposed between the structural layer 404 and the substrate 386 during the manufacture of the mirror microstructure 384 by surface micromachining techniques. The

general design considerations for etch release rails again are summarized below following the description of the various embodiments of microstructures that include such etch release rails.

Another function provided by the plurality of rails 400 and the plurality of rails 396 is structural reinforcement of the microstructure 384 and, more particularly the structural layer 404. In the illustrated embodiment, the rails 400 provide enhanced stiffness in effectively one direction and the plurality of rails 396 provide enhanced stiffness in effectively one direction as well, but different from that associated with the rails 400. It is believed that enhanced structural reinforcement is realized by having the plurality of rails 400 disposed in a different orientation within the lateral dimension than the plurality of rails 396. In the illustrated embodiment, the plurality of rails 400 are disposed at least substantially perpendicular to the plurality of rails 396 in the lateral dimension. The structural reinforcement function of the rails 400 and 396 would not be adversely affected, and may in fact improve, by having at least some of the rails 400 be disposed in intersecting in relation and/or by having at least some of the rails 396 be disposed in intersecting relation (e.g., see Figures 9A-B).

Certain parameters are identified on one or more of Figures 10A-C in relation to the mirror microstructure 384 and that are addressed in the above-noted summarization of the desirable characteristics that follows below. The dimension "d_{SL}" for the case of the microstructure 384 represents the diameter of the structural layer 404 (e.g., the distance of a straight line that extends from one location on the perimeter 390 of the structural layer 404, through a center 388 of the structural layer 404, and to another location on this perimeter 390) that is being structurally reinforced collectively by the plurality of rails 400 and the plurality of rails 396. The dimension "d_{RS}" for the case of the microstructure 384 represents the distance from the center 388 of the structural layer 404 to that rail 400 that is closest to the center 388.

Finally, RC for the case of the mirror microstructure 384 represents the radius of curvature of the structural layer 404.

Figure 10D presents a variation of the mirror microstructure 384 of Figures 10A-C. The only difference between the Figure 10A-C and Figure 10D configurations is that the rails 400 in the Figure 10A-C configuration are replaced with a plurality of columns or posts 400' in the Figure 10D configuration. The Figure 10D configuration still provides at least some degree of structural reinforcement for the structural layer 404, and also allows for formation of etch release conduits along the length of the rails 396.

Other layouts of rails that provide/allow for the formation of the etch release conduits in a sacrificial layer(s) (i.e., etch release rails), are within the scope of the present invention. Representative examples of other etch release rail layouts that may be appropriate for forming etch release channels and that may be used in any of the above-described embodiments of mirror microstructures are presented in Figures 11A-F. Figure 11A illustrates an embodiment in which a plurality of rails 412 are fixed to and extend away from a structural layer or support 408. These rails 412 may "cantilever" from this structural layer 408, or alternatively may interconnect the structural layer 408 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In any case, the rails 412 have what may be characterized as a sinusoidal lateral dimension or a sinusoidal configuration in plan view, and further extend from one location on or at least generally proximate to a perimeter 410 (e.g., within 50 μm of this perimeter 410, more preferably within 25 μm of this perimeter 410) of the structural layer 408 to another location on or at least generally proximate to this perimeter (e.g., within 50 μm of this perimeter 410, more preferably within 25 μm of this perimeter 410). Stated another way, the plurality of rails 412 extend sinusoidally within a plane that is at least generally parallel with the

substrate 408. In the illustrated embodiment, none of the rails 412 intersect and adjacent rails 412 are nested to a degree such that the peaks 416 of one rail 412 extend at least partially within the space defined by a corresponding trough 420 of the adjacent rail 412. Stated another way, the peaks 416 of one rail 412 preferably extend beyond a line that is tangent to the troughs 420 of an adjacent rail 412. The "amplitude" of this sinusoidal configuration need not remain constant along the length of the rails 412. The rails 412 also may be characterized as "meandering" so as to provide enhanced stiffness in more than one dimension. Other "meandering" configurations than the sinusoidal type illustrated in relation to Figure 11A may be utilized as well for structural reinforcement and to allow for the formation of etch release channels (e.g., in zig-zag fashion).

Figure 11B illustrates an embodiment in which a plurality of rails 436 are fixed to and extend away from a structural layer or support 424. These rails 436 may "cantilever" from this structural layer 424, or alternatively may interconnect the structural layer 424 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In any case, instead of being disposed in parallel relation, the plurality of rails 436 are at least generally radially disposed or extending (but still within the lateral dimension). In the illustrated embodiment, the plurality of rails 436 extend from or at least generally proximate to a perimeter 428 (e.g., within 50 μm of this perimeter 428, more preferably within 25 μm of this perimeter 428) of the structural layer 424 toward, but not to, a center 432 of the structural layer 424.

Figure 11C illustrates an embodiment in which a plurality of rails 452, 456 are fixed to and extend away from a structural layer or support 440. These rails 452, 456 may "cantilever" from this structural layer 440, or alternatively may interconnect the structural layer 440 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In any case, instead of being disposed in parallel relation, the plurality of rails 452, 456 are at least

generally radially disposed or extending (but still within the lateral dimension). In the illustrated embodiment, the plurality of rails 452, 456 extend from or at least generally proximate to a perimeter 444 (e.g., within 50 μm of this perimeter 444, more preferably within 25 μm of this perimeter 444) of the structural layer 440 at least toward a center 448 of the structural layer 440. The rails 452 extend further toward the center 448 than the rails 456. This reduces the potential for adversely affecting the formation of the etch release channels at radially inward locations (i.e., at locations that are closer to the center 448).

Figure 11D illustrates an embodiment in which a plurality of first rails 508 and a plurality of second rails 512 are fixed to and extend away from a structural layer or support 500. These rails 508, 512 may "cantilever" from this structural layer 500, or alternatively may interconnect the structural layer 500 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In any case, instead of being disposed in parallel relation, the plurality of first rails 508 and the plurality of second rails 512 are at least generally radially disposed or extending (but still within the lateral dimension). In the illustrated embodiment, the plurality of first rails 508 and the plurality of second rails 512 extend from or at least generally proximate to a perimeter 504 (e.g., within 50 μm of this perimeter 504, more preferably within 25 μm of this perimeter 504) of the structural layer 500 toward, but not to, a center 506 of the structural layer 500. Generally, the plurality of first rails 508 extend further toward the center 506 than do the plurality of second rails 512, and at least one second rail 512 is disposed between adjacent pairs of first rails 508.

Figure 11E illustrates an embodiment in which a plurality of first rails 528, second rails 532, third rails 540, and fourth rails 548 are fixed to and extend away from a structural layer or support 516. Although these rails 528, 532, 540, and 548 are illustrated as being simply a line in

Figure 11E, it should be appreciated that these rails 528, 532, 540, and 548 may be of any appropriate width. These rails 528, 532, 540, and 548 may "cantilever" from this structural layer 516, or alternatively may interconnect the structural layer 516 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In the illustrated embodiment, all of the rails 528, 532, 540, and 548 are not disposed in parallel relation to each other, and furthermore all of the rails 528, 532, 540, and 548 are not radially disposed or extending within the lateral dimension (i.e., all rails 528, 532, 540, and 548 do not extend toward a point corresponding with a center 524 of the structural layer 516). Instead, in the illustrated embodiment: 1) the plurality of first rails 528 extend from or at least generally proximate to a perimeter 520 (e.g., within 50 μm of this perimeter 520, more preferably within 25 μm of this perimeter 520) of the structural layer 516 to a point corresponding with the center 524 of the structural layer 516 - that is, the rails 528 intersect at a point corresponding with the center 524, and effectively define a column or post that is disposed at the center 524; 2) a pair of second rails 532 are disposed between each adjacent pair of first rails 528, and extend from or at least generally proximate to the perimeter 520 (e.g., within 50 μm of this perimeter 520, more preferably within 25 μm of this perimeter 520) of the structural layer 516 to an intersection 536 - that is, a pair of second rails 532 that terminate at an intersection 536 are "nested" between each adjacent pair of first rails 528; 3) a pair of third rails 540 are disposed within the space that is inward of each pair of second rails 532 that are joined at an intersection 536, and extend from or at least generally proximate to the perimeter 520 (e.g., within 50 μm of this perimeter 520, more preferably within 25 μm of this perimeter 520) of the structural layer 516 to an intersection 544 - that is, a pair of third rails 540 that terminate at an intersection 544 are "nested" between each adjacent pair of second rails 532 that are joined at an intersection 536; and 4) a pair of fourth

rails 548 are disposed within the space that is inward of each pair of third rails 540 that are joined at an intersection 544, and extend from or at least generally proximate to the perimeter 520 (e.g., within 50 μm of this perimeter 520, more preferably within 25 μm of this perimeter 520) of the structural layer 516 to an intersection 552 - that is, a pair of fourth rails 548 that terminate at an intersection 552 are "nested" between each adjacent pair of third rails 540 that are joined at an intersection 544. Therefore, the layout presented in Figure 11E has at least some etch release rails that intersect at one common point (e.g., rails 528 that intersect at a point corresponding with the center 524), while other rails intersect at a different common point (e.g., at intersections 536, 544, 552).

Figure 11F illustrates an embodiment in which a plurality of first rails 568, second rails 572, third rails 576, and fourth rails 580 are fixed to and extend away from a structural layer or support 556. These rails 568, 572, 576, and 580 may "cantilever" from this structural layer 556, or alternatively may interconnect the structural layer 556 with another structural layer (not shown) to provide a multi-layered mirror microstructure. In any case, instead of being disposed in parallel relation, the plurality of rails 568, 572, 576, and 580 are at least generally radially disposed or extending (but still within the lateral dimension). That is, the plurality of rails 568, 572, 576, and 580 extend from or at least generally proximate to a perimeter 560 (e.g., within 50 μm of this perimeter 560, more preferably within 25 μm of this perimeter 560) of the structural layer 556 at least toward a point corresponding with a center 564 of the structural layer 556. Generally, the rails 568, 572, 576, and 580 terminate at different radial positions relative to the center 564 of the structural layer 556. In the illustrated embodiment: 1) the plurality of first rails 568 extend from or at least generally proximate to the perimeter 560 (e.g., within 50 μm of this perimeter 560, more preferably within 25 μm of this perimeter 560) of the structural layer 556 to

the center 564 of the structural layer 556 - that is, the plurality of first rails 568 intersect at a common point corresponding with the center 564, and effectively define a column or post that is disposed at the center 564; 2) one second rail 572 is disposed between each adjacent pair of first rails 568, and extends from or at least generally proximate to the perimeter 560 (e.g., within 50 μm of this perimeter 560, more preferably within 25 μm of this perimeter 560) of the structural layer 556 toward, but not to, the center 564 of the structural layer 556; 3) one third rail 576 is disposed between each first rail 568 and an adjacent second rail 572, and extends from or at least generally proximate to the perimeter 560 (e.g., within 50 μm of this perimeter 560, more preferably within 25 μm of this perimeter 560) of the structural layer 556 toward, but not to, the center 564 of the structural layer 556; and 4) one fourth rail 580 is disposed between each pair of adjacent rails 568, 572, and 576, and extends from or at least generally proximate to the perimeter 560 (e.g., within 50 μm of this perimeter 560, more preferably within 25 μm of this perimeter 560) of the structural layer 556 toward, but not to, the center 564 of the structural layer 556. The second rails 572 extend further toward the center 564 than the third rails 576, and the third rails 576 extend further toward the center 564 than the fourth rails 580.

Various layouts of etch release rails have been described above. However, it should be appreciated that these layouts are merely representative of the various ways in which etch release rails may be patterned to define a plurality of etch release conduits. Any layout of etch release rails may be utilized that will allow for the removal of one or more sacrificial layers in a desired manner by providing or allowing for the formation of a plurality of at least generally laterally extending etch release conduits or channels within one or more sacrificial layers through which an appropriate etchant may flow during the release of the corresponding microstructure from its substrate. What etch release rail layouts are appropriate for this purpose is based upon a number

of factors. Generally, the etchant will proceed at least generally perpendicularly away from its corresponding etch release conduit. At least one and more typically a pair of etch release conduits will extend at least generally along the lateral extent of each etch release rail. A targeted total etch release time will be established or specified. The maximum total etch release time for the types of microstructures described herein is preferably that which does not significantly damage any of the structural layers of the corresponding microstructure by exposure of the same to the etchant. The etch rate will also be known and for design purposes may be assumed to be constant. Therefore, a determination may then be made as to how far from a given etch release conduit the etchant will proceed in the specified total etch release time to create what may be characterized as a projected etch release void. So long as the projected etch release voids between adjacent etch release rails abut or more preferably overlap to a degree, or stated another way such that the entirety of the space between adjacent etch release rails is defined by at least one and more typically a plurality of projected etch release voids, the proposed layout of the etch release rails will be appropriate for affecting the release.

Another way to characterize an appropriate layout of etch release rails is in relation to a maximum desired spacing between adjacentmost etch release rails. Each etch release rail should be positioned such that the maximum space between a given etch release rail and an adjacentmost etch release rail is no more than about twice the linear distance that an etchant will proceed through a sacrificial layer in a specified total etch release time. In one embodiment, this maximum spacing is less than about 100 microns, and in another embodiment is within a range of about 50-75 microns.

Another important factor in relation to the various mirror microstructures discussed above, as well as in relation to the methods and mirror microstructures to be discussed below, is

the surface topography of the uppermost structural layer of these mirror microstructures. This is particularly an issue when reinforcing structures extend or depend from the lower surface of this uppermost structural layer. These types of structures are generally formed by first forming a plurality of apertures within a layer of sacrificial material, and then depositing a structural material over this layer of sacrificial material (discussed in more detail below). That portion of the structural material that is deposited within the apertures formed in the layer of sacrificial material defines the reinforcing structures. The surface topography that is desired for the upper surface of the uppermost structural layer of any of the mirror microstructures described herein, as deposited, or stated another way before being planarized, is one where the maximum distance between any peak and valley on the upper surface of this uppermost structural layer is less than the maximum thickness of this uppermost structural layer. This type of surface topography allows the upper surface of the uppermost structural layer to thereafter be planarized a reasonable amount to yield the desired degree of optical flatness.

There are a number of ways in which the desired surface topography can be realized for the case where reinforcing structures extend from the lower surface of the uppermost structural layer of the mirror microstructure. One is to form this uppermost structural layer for the mirror microstructure to a sufficient thickness such that appropriate planarization techniques (e.g., chemical mechanical polishing) may be utilized to reduce the surface roughness of this surface to a desired level without an undesirable amount of thinning of this uppermost structural layer at any location. A sufficient thickness for the uppermost structural layer in this scenario is where the thickness of the uppermost structural layer is thicker than the underlying layer of sacrificial material by an amount such that after being planarized (e.g., by chemical mechanical polishing) to realize the desired optical surface, the uppermost structural lay will still have sufficient

mechanical integrity. Another option for the case when the thickness of the uppermost structural layer of the mirror microstructure is comparable to the thickness of the underlying layer of sacrificial material is to control the width of the apertures in this layer of sacrificial material that again are used to define the reinforcing structures that extend or depend from the lower surface of the uppermost structural layer of the mirror microstructure.

The mirror microstructures described herein that structurally reinforce the uppermost structural layer, that have one or more structures extending or depending from the lower surface of the uppermost structural layer for purposes of providing etch release rails, or both, have a desired surface topography on the uppermost structural layer. This may be provided or realized by the sizing of the structures that extend or depend from the lower surface of the uppermost structural layer. Generally, the maximum width of any individual structure that extends or depends from the lower surface of the uppermost structural layer (e.g., the width of a rail, the diameter of a post or column) should be less than twice the thickness of the uppermost structural layer to provide the desired surface topography based solely on the selection of reinforcement structure width. This "thickness of the uppermost structural layer" is that thickness that is disposed above the depending reinforcing structure, or stated another way the thickness at a location that is between any adjacent depending reinforcing structures. This provides a desirable surface topography for the uppermost structural layer, namely one that may be planarized (e.g., by chemical mechanical polishing) a reasonable amount to yield a desired degree of optical flatness while allowing the uppermost structural layer to retain sufficient mechanical integrity. These same principles may be applied to any underlying structural layer of the mirror microstructure as well to improve the surface topography. It should be noted that the maximum width of the reinforcing structures that extend or depend from the lower surface of the uppermost

structural layer becomes less important as the ratio of the thickness of the uppermost structural layer to the thickness of the underlying sacrificial layer increases. Therefore, some combination of structural layer thickness and reinforcement structure width may provide the noted desired surface topography as well.

The various reinforcing structures discussed above may be used at any level within a mirror microstructure. That is, even though a particular reinforcing structure may have only been described herein in relation to a two-layered structure does not mean that the same could not be used to structurally reinforce a single structural layer of a mirror microstructure (i.e., so as to cantilever from the same) or to structurally interconnect adjacent but spaced structural layers in a mirror microstructure having three or more spaced structural layers. Moreover, any combination of the above-noted reinforcing structures may be used in any combination in a microstructure having three or more spaced structural layers (e.g., to interconnect any two adjacent but spaced structural layers), or may cantilever from a lower surface of a structural layer to structurally reinforce the same in the general manner, for instance, of the microstructure 302 to be discussed below in relation to the methodology of Figures 15A-G.

The above-noted reinforcing structures may also utilize any appropriate vertical and/or horizontal cross-sectional profiles/configurations, and further may extend in the lateral dimension in any appropriate manner (e.g., axially, sinusoidally, meandering, "zig-zagging"). Although the above-noted reinforcing structures have been illustrated as being at least generally perpendicular to an interconnected structural layer(s), such need not be the case. Moreover, all reinforcing structures need not necessarily be disposed in the same vertical orientation (i.e., the same may be disposed at one or more different angles relative to vertical).

It should be appreciated that the mirror microstructures 30, 58, 106, 130, 166, 384, and 384' discussed above may be incorporated into any surface micromachined system and at any elevation within such a system, and that these microstructures 30, 58, 106, 130, 166, 384, and 384' may be appropriate for applications other than as a mirror. Characterizing the various structural layers in these microstructures 30, 58, 106, 130, 166, 384, and 384' as "first," "second" and the like also does not necessarily mean that these are the first, second, or the like structural layers that are deposited over the associated substrate, although such may be the case. It should also be appreciated that the characterization of the various structural layers of these microstructures 30, 58, 106, 130, 166, 384, and 384' as "first," "second," and the like also does not mean that the same must be "adjacent" structural layers in any surface micromachined system that includes these microstructures 30, 58, 106, 130, 166, 384, and 384'. There may be one or more intermediate structural layers that are deposited over the associated substrate at an elevation that is between what has been characterized as "first" and "second" structural layers or the like, although any such structural layers will have been removed from the area occupied by the microstructures 30, 58, 106, 130, 166, 384, and 384' (e.g., there may be one or more of structural layers that are "off to the side" or laterally disposed relative to a given microstructure for various purposes). It should also be appreciated that the various structural layers of the noted microstructures 30, 58, 106, 130, 166, 384, and 384' may also be defined by one or more structural layers, such as involving multiple and spaced in time depositions.

One key advantage of the microstructures 30, 58, 106, 130, 166, 384, and 384' discussed above is their structurally reinforced nature. Some of these reinforcement alternatives may require etch release holes through one or more of the various structural layers depending upon the particular manufacturing technique that is employed, which may degrade the performance of

the microstructures 30, 58, 106, 130, 166, 384, and 384' in a given application (e.g., when functioning as a mirror in an optical system, and where etch release holes are required for the uppermost structural layer because of the reinforcement structure that was utilized). A certain amount of degradation may be acceptable based upon the enhanced structural rigidity realized by these microstructures, and in certain applications the existence of the noted etch release holes may be irrelevant or at least of reduced significance. However, certain of the reinforcement structures utilized by the above-noted microstructures may actually enhance the release of the microstructure from the associated substrate and altogether alleviate the need for vertically disposed etch release holes in one or more structural layers. These techniques will be discussed in more detail below in relation to Figures 12-15, 17, and 20.

The above-described structurally reinforced mirror microstructures will typically have a minimum surface area of about 2,000 μm^2 with a minimum lateral dimension of about 50 μm for the optically functional surface of the mirror microstructure (e.g., in the case of a circular mirror microstructure, this minimum lateral dimension would be its diameter; in the case of a square mirror microstructure, this minimum lateral dimension would be the length of any of its four sides; in the case of a rectangular mirror microstructure, this minimum lateral dimension would be the length of the shortest of its four sides). Moreover, the above-described structurally reinforced mirror microstructures will utilize a structural layer with the optically functional surface that has a maximum film thickness of about 10 μm in one embodiment, and more typically about 6 μm in another embodiment. This "maximum film thickness" does not include the thickness of any reinforcement structure that extends or depends from a lower surface of the relevant structural layer.

The actual amount by which the above-noted microstructures are structurally reinforced is affected by one or more characteristics of the reinforcing structures that are used. There may be two extremes in relation to the number or density of reinforcing structures that are used. The first is having a high density for the individual reinforcing structures, which is limited only by the design rules and minimum dimensions of the process technology, as well as the ability to insure that the etchant for the release can adequately access the sacrificial films for their removal. The second extreme is to go to a very sparse or low density for the reinforcing structures, which gets to the point of doing limited reinforcing or stiffening of the associated structural layer(s). The benefit of the former is to provide a maximum effect of reinforcement or stiffening of the associated structural layer(s) or microstructure, but at the expense of density and therefore total mass of the microstructure (i.e., in the case where the microstructure is a mirror, the microstructure may be very stiff, but too massive to allow for the use or realization of rapid switching speeds). Therefore, the optimum spacing and size of the reinforcing structures will oftentimes be an engineering compromise between stiffness and mass. If total mass does not matter, but stiffness is at a premium, then using a high density for the reinforcing structures, as allowed by the design and processed rules, would be optimum for the particular application. However, if the microstructure is a mirror or some other structure which must switch or otherwise move at a relatively fast rate (e.g., in sub-millisecond times), then a calculation of total mass versus available actuation forces will likely determine the appropriate density for the reinforcing structures. Mass may also be an issue for those microstructures that are moved in relation to the physical size of any associated actuator, the amount of voltage required to accomplish the desired movement, or both.

There are a number of ways in which the microstructures 30, 58, 106, 130, 166, 384, and 384' may be at least generally characterized. One or more of the microstructures 30, 58, 106, 130, 166, 384, and 384' may be characterized as including: 1) at least two separate and distinct (i.e., not interconnected and disposed in spaced relation) reinforcing structures (e.g., at least two separate and discrete columns or posts; at least two separate and discrete rails); 2) at least two separate and distinct reinforcing structures that are disposed at different and radially spaced locations or positions in the lateral dimension, or at least two different portions of what may be characterized as a single reinforcing structure (e.g., the "grid" defined by the rails 174 and rails 178 in the microstructure 166 of Figures 9A-B) being disposed at different and radially spaced locations or positions in this lateral dimension; 3) having a ratio of d_{RS}/d_{SL} that is no more than about 0.5, and thereby including a ratio of "0", for instance where d_{RS} is "0" (i.e., where there is a reinforcing structure at the center of the structural layer being structurally reinforced); or 4) or any combination thereof. Visualization of the second noted characterization may be enhanced by a reference to the Figure 2-3 embodiment where at least some of the plurality of columns 50 of the microstructure 30 are clearly disposed at a different distance from a center 42 of the microstructure 30, as well as the Figure 9A-B embodiment where at least some of the rails 174 and at least some of the rails 178 are disposed at different radial positions and are in spaced relation.

Another way of characterizing the microstructures 30, 58, 106, 130, 166, 384, and 384' is in relation to a radius of curvature RC of the uppermost structural layer (e.g., the amount by which the uppermost structural layer is "bowed" or "dished"). The radius of curvature RC may have its center on either side of the uppermost structural layer in the microstructures 30, 58, 106, 130, 166, 384, and 384'. That is, the upper surface of the uppermost structural layer in the

microstructures 30, 58, 106, 130, 166, 384, and 384' may be generally concave or generally convex. In one embodiment, the uppermost structural layer of the microstructures 30, 58, 106, 130, 166, 384, and 384' has a radius of curvature RC that is at least about 1 meter, and in another embodiment that is at least about 2 meters. The reinforcement configuration used by the microstructure 166 in a three-layered mirror microstructure has been fabricated with a radius of curvature RC that is about 14 meters. It should be noted that increasing the stiffness of a microstructure does not in and of itself mean that the radius of curvature of an uppermost structural layer of this microstructure will in turn be increased. That is, the case of a constant stress gradient through a plate or a beam leads to the same radius of curvature independent of thickness to first order. This then indicates that simple stiffening by adding thickness to a plate or a beam does not, in and of itself, necessarily lead to a flatter structure with a greater radius of curvature. However, the complex method of reinforcing microstructures in the manner disclosed herein can lead to significant internal stress compensation between and within the individual structural layers of these reinforced microstructures, such that greater flatness (i.e., a larger radius of curvature for the uppermost structural layer) can be realized in addition to achieving greater stiffness.

Another characterization that can be made in relation to the microstructures 30, 58, 106, 130, 166, 384, and 384' is the effect of the various reinforcing structures/layouts on overall structural stiffness of the microstructures 30, 58, 106, 130, 166 384, and 384', which can be characterized by moment of inertia. In very general terms, the moment of inertia for a simple rectangular cross-section is $I=bh^3/12$, where h is the plate thickness and b the width. This illustrates the general idea or concept that structural stiffness is a cubic function of the corresponding thickness. Thus, going from a 2.25 μm thick single structural layer to an

approximately 11.0 μm multi-layered, structurally reinforced microstructure of the type contemplated by the microstructures 30, 58, 106, 130, 166, 384, and 384' implies an approximate increase of stiffness by a factor of $11^3/2.25^3 = 117$, or roughly two orders of magnitude (with the orders by 10-based). This is important when there is a need for a structure to not deform out of plane, or in the case of a mirror microstructure that is coated with a reflective gold layer to not be deformed by the stress in the gold layer. In other words, because of thermal mismatch for example, the gold can be in relative tension to the underlying structural layer (e.g., polysilicon), and thus would have the tendency to cause the underlying structural layer to curl into a cup shape. The dramatic increase in stiffness by reinforcement will keep the mirror microstructure much flatter. Also, during temperature cycles, the gold-coated plate will not change its RC as much (i.e., it will be much more mechanically stable). The overall complexity of the geometry and the deposition and anneal precludes a simple 'estimate' of the resulting RC especially at the current levels being obtained. Empirical determination is less time consuming and more accurate.

Investigations are still being undertaken in relation to evaluating the structural reinforcement of the microstructures 30, 58, 106, 130, 166, 384, and 384'. Generally, it is believed that a structurally reinforced three-layered microstructure will be more rigid than a structurally reinforced two-layered microstructure. In this case, any combination of the above-noted reinforcing structures that structurally interconnect adjacent structural layers in the microstructures 30, 58, 106, 130, 166, 384, and 384' may be utilized in a three-layered microstructure in accordance with one or more principles of the present invention. However, evaluations are still ongoing in relation to "optimizing" the structural reinforcement of the microstructures 30, 58, 106, 130, 166, 384, and 384' in the general manner described herein.

There may be instances where different combinations of the above-noted reinforcing structures may be more appropriate for when the associated microstructure is used in a given application or in certain conditions.

Various microstructure fabrication methods will now be described. Each of the various fabrication methods to be discussed that utilize reinforcement/etch release rails may also use the above-noted guidelines for maximum reinforcement structure widths to realize the desired surface topography for the uppermost structural layer prior to planarizing the same. Each of the various fabrication methods to be discussed which define etch release conduits should be implemented such that at least one end of at least one etch release conduit is disposed at or at least generally proximate to a perimeter of the microstructure being fabricated (e.g., within 50 microns of this perimeter in one embodiment, and more preferably within 25 microns of this perimeter in another embodiment). This again reduces the amount of time that the release etchant must "etch in" from this perimeter before reaching the etch release conduit(s), and thereby allows the release to be finished within a desired amount of time. Multiple ends of etch release conduits or etch release conduit accesses are preferably disposed at this radial position. It should be noted that sacrificial material is disposed about the perimeter of the microstructures that are fabricated in accordance with the following. Therefore, absent a preformed via or the like, the release etchant must first etch down to the level(s) at which the etch release conduits are disposed. However, the time required for the release etchant to go down to the level(s) of the etch release conduits is not that significant due to the rather minimal vertical distance which these microstructures extend above their corresponding substrate.

One method for making a microstructure is illustrated in Figures 12A-M. This methodology may be utilized to make the mirror microstructure 106 of Figures 5-6, and the

principles of this methodology may be utilized in/adapted for the manufacture of the mirror microstructure 130 of Figure 7, the mirror microstructure 384 of Figures 10A-C, and the mirror microstructure 384' of Figure 10D, as well as the variations therefore that are presented in Figures 11A-F. In addition to being able to form a desired reinforcing structure, the methodology of Figures 12A-M further provides a desired manner for releasing the microstructure at the end of processing by forming a plurality of at least generally laterally extending etch release conduits in one or more of its sacrificial layers to facilitate the removal thereof to provide the releasing function.

Figure 12A illustrates a substrate 182 on which a microstructure 180 (Figure 12M) will be fabricated by surface micromachining techniques. Multiple layers are first sequentially deposited/formed over the substrate 182. A first sacrificial layer 186 is deposited over the substrate 182 as illustrated in Figure 12B, a first structural layer 190 is deposited on the first sacrificial 186 as illustrated in Figure 12C, and a second sacrificial layer 194 is deposited on the first structural layer 190 as illustrated in Figure 12D. The second sacrificial layer 194 is then patterned to define a plurality of interconnect apertures 198 as illustrated in Figure 12E. These interconnect apertures 198 at a minimum allow for establishing a structural connection with the first structural layer 190, and may be in the form of at least generally laterally extending grooves or trenches (e.g., to define a plurality of rails or at least the lower portion thereof, such as the type utilized by the mirror microstructure 106 of Figure 5, the mirror microstructure 130 of Figure 7, and the mirror microstructure 384 of Figure 10A, as well as the variations therefore illustrated in Figures 11A-F). These interconnect apertures 198 could also be in the form of a plurality of separate and discrete holes that are disposed in spaced relation to define a plurality of posts or columns that would structurally interconnect with the underlying first structural layer

190 (e.g., similar to the manner in which the columns 50 interconnect with the underlying first structural layer 34 in the case of the mirror microstructure 30 of Figure 2A). Using the methodology of Figures 12A-M to make the mirror microstructure 384 of Figures 10A-C or the mirror microstructure 384' of Figure 10D would not require this type of a patterning of the second sacrificial layer 194 to define the plurality of interconnect apertures 198, since the rails 396 of the microstructure 384/384' do not interconnect with any underlying structural layer.

A second structural layer 202 is deposited on the second sacrificial layer 194 as illustrated in Figure 12F. The material that defines the second structural layer 202 is also deposited within and at least substantially fills the interconnect apertures 198 that were previously formed in the second sacrificial layer 194, and such may be characterized as being part of the second structural layer 202. This portion of the second structural layer 202 may be characterized as a plurality of first reinforcement sections 214 that will be the lower extreme of a reinforcing assembly 208 for the microstructure 180 that is being fabricated. Although Figure 12F shows an intersection between the lower extreme of each of the first reinforcement sections 214 and the upper extreme of the first structural layer 190, typically such an intersection will not exist and instead will at least appear to be continuous.

The second structural layer 202 is then patterned to define a plurality of at least generally laterally extending second reinforcement sections 210 for the reinforcing assembly 208, as illustrated in Figure 12G (e.g., to define a plurality of rails or at least the middle portion thereof of the type utilized by the microstructure 106 of Figure 5, the microstructure 130 of Figure 7, the microstructure 384 of Figures 10A-C, and the microstructure 384' of Figure 10D, as well as the variations therefore presented in Figures 11A-F). Each second reinforcement section 210 is disposed directly above (e.g., vertically aligned) with at least one first reinforcement section 214

(if used), although the second reinforcement sections 210 will typically have a slightly larger width than any corresponding first reinforcement section(s) 214.

A third sacrificial layer 218 is then deposited on the second reinforcement sections 210 that were formed from the second structural layer 202 as illustrated in Figure 12H. The upper surface of this third sacrificial layer 218 will typically have a wavy or uneven contour. Generally, those portions of the third sacrificial layer 218 that are disposed over the second reinforcement sections 210 will be disposed at a higher elevation than those portions of the third sacrificial layer 218 that are disposed between adjacent second reinforcement sections 210. Therefore, the upper surface of the third sacrificial layer 218 will typically be planarized in an appropriate manner, such as by chemical mechanical polishing to yield a sufficiently flat upper surface for the third sacrificial layer 218, as illustrated in Figure 12I.

The third sacrificial layer 218 is then patterned to define a plurality of interconnect apertures 222 as illustrated in Figure 12J. These interconnect apertures 222 at a minimum allow for establishing a structural interconnection with the second reinforcement sections 210, and may be in the form of at least generally laterally extending grooves or trenches (e.g., to define a plurality of rails or at least the upper portion thereof of the type utilized by the microstructure 106 of Figure 5, the microstructure 130 of Figure 7, and the microstructure 384 of Figure 10A, as well as the variations therefore illustrated in Figures 11A-F), or may be in the form of a plurality of separate and discrete holes that are disposed in spaced relation (e.g., to define a plurality of posts or columns of the type utilized by the mirror microstructure 384' of Figure 10D). Each interconnect aperture 222 is disposed directly above (e.g., vertically aligned) a corresponding second reinforcement section 210, although the second reinforcement sections 210 will typically have a slightly larger width than their corresponding interconnect aperture(s) 222.

A third structural layer 226 is deposited on the third sacrificial layer 218 as illustrated in Figure 12K. The material that defines the third structural layer 226 is also deposited within and at least substantially fills the interconnect apertures 222 that were previously formed in the third sacrificial layer 218, and such may be characterized as being part of the third structural layer 226. This portion of the third support layer 226 may be characterized as a plurality of third reinforcement sections 230 that are the upper extreme of the reinforcing assembly 208 for the microstructure 180 that is being fabricated. Although Figure 12K shows an intersection between the lower extreme of each of the third reinforcement section 230 and the upper extreme of their corresponding second reinforcement 210, typically such an intersection will not exist and instead will at least appear to be continuous.

The upper surface of the third structural layer 226 will typically have a wavy or uneven contour as illustrated in Figure 12K. Generally, those portions of the third structural layer 226 that are disposed between adjacent third reinforcement sections 230 will be recessed to a degree. Therefore, the upper surface of the third structural layer 226 will typically be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the third structural layer 226 as illustrated in Figure 12L. This completes the definition of the microstructure 180. It should be appreciated that the system that includes the microstructure 180 will likely include other components than those illustrated in Figures 12A-M and that may interface with the microstructure 180 in some manner (e.g., one or more actuators).

The microstructure 180 is now ready to be released. "Released" means to remove each of the sacrificial layers of the surface micromachined system and thereby including the first sacrificial layer 186, the second sacrificial layer 194, and the third sacrificial layer 218. An etchant is used to provide the releasing function. The manner in which the microstructure 180

was formed in accordance with the methodology of Figures 12A-M reduces the time required for the sacrificial layers 194 and 218 to be totally removed. Ultimately, a plurality of at least generally laterally extending etchant flow pipes, channels, or conduits are formed in the third sacrificial layer 218. Those portions of the third sacrificial layer 218 that are positioned against/near the second reinforcement sections 210 that were formed from the second structural layer 202 are believed to be less dense than the remainder of the third sacrificial layer 218 since the etch rate is greater in proximity to the second reinforcement sections 210 and including along the length thereof. Recall that the third sacrificial layer 218 was deposited after the second reinforcement sections 210 were formed, which creates these low density regions. Low density regions in the third sacrificial layer 218 thereby exist along the entire length of both sides of each second reinforcement 210. Principally these low density regions will exist along a sidewall 212 of each of the second reinforcement section 210 (e.g., the vertically disposed/extending portion of the second reinforcement section 210). The etch rate will be greater in the low density regions of the third sacrificial layer 218 than throughout the remainder of the third sacrificial layer 218. This will effectively form at least two etch release pipes, channels or conduits in the third sacrificial layer 218 along the side of each second reinforcement section 210. The development of the etch release channels during the initial portion of the release etch provides access to interiorly disposed locations within the sacrificial layers for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 180. Notwithstanding the characterization of the structures 214, 210, and 230 as "reinforcement sections," it should be appreciated that the entire focus of the methodology of Figures 12A-M could in fact be to simply provide a plurality of at least generally laterally extending etch release conduits, to in turn provide a "rapid etch release function" for the microstructure 180. That is, it is not required that

the structures 214, 210, and 230 actually structurally reinforce the microstructure 180, although such is preferably the case. Therefore, the structures 210 that provide for the definition of the low density regions in the third sacrificial layer 218, and thereby the etch release conduits, could also be properly characterized as etch release rails or the like.

The microstructure 180 of Figure 12M has a desired surface topography on its third structural layer 226 using the above-noted principles. For the case where the thickness of third structural layer 226 is comparable or less than the thickness of the underlying third sacrificial layer 218, the maximum lateral dimension of any rail upper section 230 (designated as "w" in Figure 12M) again should be less than twice the thickness of the uppermost structural layer (designated as "t" in Figure 12M, and which does not include the depending structure). This again provides a desirably smooth surface topography for the third structural layer 226, which is desired for optical applications. Having the third structural layer 218 be of a thickness which is greater than the thickness of the third sacrificial layer 218 reduces the effects of the width of the interconnect apertures 222 on the surface topography of the third structural layer 218.

The basic principle for forming etch release channels or conduits encompassed by the methodology represented in Figures 12A-M is that low density regions of sacrificial material are formed when the sacrificial material is deposited along at least generally vertically disposed surfaces of an etch release rail, and that the same each effectively defines a etch release channel or conduit. These etch release rails may exist at any desired level within the microstructure being fabricated and yet still provide this low density region formation function. Moreover, these etch release rails do not need to be structurally interconnected with the uppermost structural layer of the microstructure being fabricated to provide this low density region formation function. For instance, these etch release rails instead could be anchored to the

underlying substrate or another underlying structural layer. In fact, these etch release rails need not remain in the final structure of the microstructure being fabricated at all, but instead may be removed during the release of the microstructure from the substrate.

Another method for making a microstructure is illustrated in Figures 13A-M. This methodology may be utilized to make the mirror microstructure 106 of Figures 5-6, and the principles of this methodology may be utilized in/adapted for the manufacture of the mirror microstructure 130 of Figure 7, the mirror microstructure 384 Figures 10A-C, and the mirror microstructure 384' of Figure 10D, as well as the variations therefore presented in Figures 11A-F. In addition to being able to form a desired reinforcing structure, the methodology of Figures 13A-M further provides a desired manner for releasing the microstructure at the end of processing by forming a plurality of at least generally laterally extending etch release conduits in one or more of its sacrificial layers to facilitate the removal thereof to provide the releasing function. In contrast to the methodology of Figures 12A-M, the methodology of Figures 13A-M forms these etch release conduits during the fabrication of the microstructure (i.e., there is at least one more deposition after these etch release conduits are formed). Stated another way, the plurality of etch release in the case of the methodology of Figures 13A-M exist before the microstructure and sacrificial layers are exposed to any etchant for providing the release function.

Figure 13A illustrates a substrate 234 on which a microstructure 232 will be fabricated. Multiple layers are first sequentially deposited/formed over the substrate 234. A first sacrificial layer 238 is deposited over the substrate 234 as illustrated in Figure 13B, a first structural layer 242 is deposited on the first sacrificial layer 238 as illustrated in Figure 13C, and a second sacrificial layer 246 is deposited on the first structural layer 242 as illustrated in Figure 13D.

The second sacrificial layer 246 is then patterned to define a plurality of interconnect apertures 250 as illustrated in Figure 13E. These interconnect apertures 250 at a minimum allow for establishing a structural connection with the first structural layer 242, and may be in the form of at least generally laterally extending grooves or trenches (e.g., to define a plurality of rails or at least the lower portion thereof of the type utilized by the microstructure 106 of Figure 5 and the microstructure 130 of Figure 7, as well as the variations therefore illustrated in Figures 11A-F). The interconnect apertures 250 could also be in the form of a plurality of separate and discrete holes that are disposed in spaced relation to define a plurality of posts or columns that would structurally interconnect with the underlying first structural layer 242 (e.g., similar to the manner in which the columns 50 interconnect with the underlying first structural layer 34 in the case of the mirror microstructure 30 of Figure 2A). Using the methodology of Figures 13A-M to make the microstructure 384 of Figures 10A-C and microstructure 384' of Figure 10D would not require this patterning of the second sacrificial layer 246 to define the plurality of interconnect apertures 250, since the rails 396 of the microstructure 384/384' do not interconnect with an underlying structural layer.

A second structural layer 254 is deposited on the second sacrificial layer 246 as illustrated in Figure 13F. The material that defines the second structural layer 254 is also deposited within and at least substantially fills the interconnect apertures 250 that were previously formed in the second sacrificial layer 246, and such may be characterized as being part of the second structural layer 254. This portion of the second support layer 254 may be characterized as a plurality of first reinforcement sections 258 that are the lower extreme of a reinforcing assembly 256 for the microstructure 232 that is being fabricated (Figure 13M). Although Figure 13F shows an intersection between the lower extreme of each of the first

reinforcement sections 258 and the upper extreme of the first structural layer 242, typically such an intersection will not exist and instead will at least appear to be continuous.

The second structural layer 254 from Figure 13F is then patterned to define a plurality of at least generally laterally extending second reinforcement sections 262 for the reinforcing assembly 256 (Figure 13M), as illustrated in Figure 13G (e.g., to define a plurality of rails or at least the middle portion thereof of the type utilized by the microstructure 106 of Figure 5, the microstructure 130 of Figure 7, the microstructure 384 of Figures 10A-C, and the mirror microstructure 384' of Figure 10D, as well as the variations therefore presented in Figures 11A-F). Each second reinforcement section 262 is disposed directly above (e.g., vertically aligned) with at least one first reinforcement section 258 (if any), although the second reinforcement sections 262 will typically have a slightly larger width than their corresponding first reinforcement section(s) 258 (if any). At this time an upper portion of the second sacrificial layer 246 is removed as illustrated in Figures 13H. That is, a portion of the second sacrificial layer 246 remains after this removal operation. The second sacrificial layer 246 extends above the first structural layer 242 a distance which is less than the distance which the lower extreme of the second reinforcement sections 262 are disposed above the first structural layer 242. As, there is now a gap or an undercut 266 beneath the lower extreme of the second reinforcement sections 262 and the upper surface of the second sacrificial layer 246. One way in which only an upper portion of the second sacrificial layer 246 may be removed is by a timed or controlled etch. It is also basically a requirement that this etch be of an isotropic type in order to form the undercuts 266. This is most easily accomplished using a liquid HF-based etchant. An anisotropic dry plasma etch, for example, would only etch straight down and the undercuts 266 (and thereby the etch release channels 270 noted below) would not subsequently be formed.

A third sacrificial layer 274 is then deposited on the second reinforcement sections 262 that were formed from the second structural layer 254 and on the second sacrificial layer 246 as illustrated in Figure 13I. Although Figure 13I shows an intersection between the third sacrificial layer 274 and the second sacrificial layer 246, typically this will not be the case such that the third sacrificial layer 274 and the second sacrificial layer 246 will appear to be continuous. Not all portions of the undercuts 266 will "fill" with the material that defines the third sacrificial layer 274, for example if the formation of the third sacrificial layer 274 is done with a PECVD oxide. These resulting voids define a plurality of at least generally laterally extending etch release channels 270. One of these etch release channels 270 is disposed on and extends along the entire length of each side of an upper extreme of the first reinforcement sections 258 of the reinforcing assembly 256 (and/or beneath the second reinforcement sections 262 along both sides thereof).

The upper surface of the third sacrificial layer 274 may retain a wavy or uneven contour after being deposited. The upper surface of the third sacrificial layer 274 may then be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the third sacrificial layer 274 and as illustrated in Figure 13I. In any case, the third sacrificial layer 274 is then patterned to define a plurality of interconnect apertures 278 as illustrated in Figure 13J. These interconnect apertures 278 at a minimum allow for establishing a structural interconnection with the second reinforcement sections 262, and may be the form of at least generally laterally extending grooves or trenches (e.g., to define a plurality of rails or at least the upper portion thereof of the type utilized by the microstructure 106 of Figure 5, the microstructure 130 of Figure 7, and the microstructure 384 of Figures 10A-C, as well as the variations therefore illustrated in Figures 11A-F), or may be in the form of a plurality of separate and discrete holes that are disposed in spaced relation (e.g., to define a plurality of posts or

columns of the type utilized by the microstructure 384' of Figure 10D). In any case, each interconnect aperture 278 is disposed directly above (e.g., vertically aligned) with a corresponding second reinforcement section 262, although the second reinforcement sections 262 will typically have a slightly larger width than their corresponding interconnect aperture(s) 278.

A third structural layer 282 is then deposited on the third sacrificial layer 274 as illustrated in Figure 13K. The material that defines the third structural layer 282 is also deposited within and at least substantially fills the interconnect apertures 278 that were previously formed in the third sacrificial layer 274, and such may be characterized as being part of the third structural layer 282. This portion of the third structural layer 282 may be characterized as a plurality of third reinforcement sections 286 that are the upper extreme of the reinforcing assembly 256 for the microstructure 232 that is being fabricated. Although Figure 13K shows an intersection between the lower extreme of each of the third reinforcement sections 286 and the upper extreme of their corresponding second reinforcement section 262, typically such an intersection will not exist and instead will at least appear to be a continuous structure.

The upper surface of the third structural layer 282 will typically have a wavy or uneven contour, such as a plurality of laterally disposed and axially extending depressions. Generally, those portions of the third structural layer 282 that are disposed between adjacent third reinforcement sections 286 will be recessed to a degree. Therefore, the upper surface of the third structural layer 282 will typically be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the third structural layer 282 and as illustrated in Figure 13L. This completes the definition of the microstructure 232. It should be appreciated that the system that includes the microstructure 232 will likely include

other components than those illustrated in Figures 13A-M and that may interface with the microstructure 232 in some manner (e.g., one or more actuators).

The microstructure 232 is now ready to be released. “Released” means to remove each of the sacrificial layers in the system, and thereby including the first sacrificial layer 238, the second sacrificial layer 246, and the third sacrificial layer 274. An etchant is used to provide the releasing function. Predefined flow paths for this etchant are defined in and extend through portions of the second sacrificial layer 246 and the third sacrificial layer 274 in the form of the above-noted etch release channels 270. The existence of the etch release channels 270 provides access to interiorly disposed locations within the sacrificial layers 246, 274 for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 232. Notwithstanding the characterization of the structures 258, 262, and 286 as "reinforcement sections," it should be appreciated that the entire focus of the methodology of Figures 13A-M could in fact be to simply provide a plurality of at least generally laterally extending etch release conduits, to in turn provide a "rapid etch release function" for the microstructure 232. That is, it is not required that the structures 258, 262, and 286 actually structurally reinforce the microstructure 232, although such is preferably the case. Therefore, the structures 258 and/or 262 that provide for the definition of the etch release conduits 270 could also be properly characterized as etch release rails or the like.

The basic principle for forming etch release channels or conduits encompassed by the methodology represented in Figures 13A-M is that one or more undercuts may be formed under an etch release rail in such a manner that the subsequent deposition of a sacrificial material will not entirely fill these undercuts, thereby leaving a void that defines an etch release channel or conduit. These etch release rails may exist at various levels within the microstructure being

fabricated and yet still allow for the formation of etch release channels or conduits in this same general manner. Moreover, these etch release rails do not need to be structurally interconnected with the uppermost structural layer of the microstructure being fabricated to allow for the formation of etch release channels or conduits in this same general manner. For instance, these etch release rails instead could be anchored to the underlying substrate or another underlying structural layer. In fact, these etch release rails need not remain in the final structure of the microstructure being fabricated at all, but instead may be removed during the release of the microstructure from the substrate as in the case of the methodology of Figures 14A-F.

Another method for making another embodiment of a microstructure 358 is illustrated in Figures 14A-F. Figure 14A illustrates that a first sacrificial layer 360 has been deposited over a substrate 356, and that an intermediate layer 364 has been deposited directly on the first sacrificial layer 360. The first sacrificial layer 360 is formed from a different material than the intermediate layer 364. In one embodiment, the first sacrificial layer 360 is formed from those types of materials identified above as being appropriate for the types of sacrificial layers described herein, while the intermediate layer 364 may be materials such as silicon nitride, polygermanium, or the like. The material that is selected for the intermediate layer 364 should be at least partially soluble in the etchant that is used to remove the first sacrificial layer 360, or in a secondary etchant that does not affect the various structural layers of the microstructure 358 and that can be applied after the release etchant. For example, if polygermanium were used for the intermediate layer 364, it will not dissolve in a release etch that uses HF, but could be dissolved subsequently in a short hydrogen peroxide bath that would not adversely affect the polysilicon that may be used for the various structural layers of the microstructure 358. In any case, of the intermediate layer 364 is then patterned to define a plurality of at least generally

laterally extending strips 368 as illustrated in Figure 14B, and which function as etch release rails. As such, any of the layouts noted above for etch release rails may be utilized. However, unlike other etch release rails described herein that also provide a reinforcing function, the strips 368 will be removed during the release of the microstructure 358 that is formed by the methodology of Figures 14A-F. In order to ensure the complete removal of the strips 368, they should be of a reduced thickness. In one embodiment, the thickness or vertical extent of the silicon nitride strips 368 is no more than about 1500 Å.

At this time, part of an upper portion of the first sacrificial layer 360 is removed as illustrated in Figures 14C. Generally, a portion of the first sacrificial layer 360 is removed from under the plurality of strips 368 along both of its edges to define a gap or an undercut 370 along both edge portions of each strip 368. The entirety of the first sacrificial layer 360 remains directly under a portion of the strips 368 in the form of a pedestal or the like to support the same. One way in which only an upper portion of the first sacrificial layer 360 may be removed is by a timed or controlled etch. It is also basically a requirement that this etch be of an isotropic type in order to form the undercuts 370. This is most easily accomplished using a liquid HF-based etchant. An anisotropic dry plasma etch, for example, would only etch straight down and the undercuts 370 (and thereby the etch release channels 380 noted below) would not subsequently be formed.

A second sacrificial layer 372 is then deposited on the strips 368 and on the first sacrificial layer 360 as illustrated in Figure 14D. Although Figure 14D shows an intersection between the second sacrificial layer 372 and the first sacrificial layer 360, typically this will not be the case such that the second sacrificial layer 372 and the first sacrificial layer 360 will appear to be continuous. Not all portions of the undercuts 370 will "fill" with the material that defines

the second sacrificial layer 372, for example if the formation of the second sacrificial layer 372 is done with a PECVD oxide. These resulting voids define a plurality of at least generally laterally extending etch release channels 380. One of these etch release channels 380 is disposed on and extends along the entire length of each bottom side portion of each of the strips 368.

The upper surface of the second sacrificial layer 372 may retain a wavy or uneven contour after being deposited (not shown). The upper surface of the second sacrificial layer 372 may then be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the third sacrificial layer 372 and as illustrated in Figure 14D. In any case, a first structural layer 376 is deposited on the second sacrificial layer 372 as illustrated in Figure 14E which defines the entirety of a microstructure 358. It should be appreciated that the system that includes the microstructure 358 will likely include other components than those illustrated in Figures 14A-F and that may interface with the microstructure 358 in some manner (e.g., one or more actuators).

The microstructure 358 is now ready to be released. "Released" means to remove each of the sacrificial layers in the system, and thereby including the first sacrificial layer 360 and the second sacrificial layer 372. The plurality of strips 368 are also removed in this release. Etchants are used to provide the releasing function. Predefined flow paths for this etchant are defined in and extend through portions of the second sacrificial layer 372 and the first sacrificial layer 360 in the form of the above-noted etch release channels 380. The existence of the etch release channels 380 provides access to interiorly disposed locations within the sacrificial layers 360, 372 for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 358.

The manner in which the etch release channels 380 are formed is similar to the methodology of Figures 13A-M. The primary difference is that the methodology of Figures 14A-F does not define any reinforcing structure for its microstructure 358, whereas the methodology of Figures 13A-M does define a reinforcing assembly 256 for its microstructure 232. A related difference is that the strips 368 in the methodology of Figures 14A-F are removed during the release etch or in a post-release etch, whereas the reinforcing assembly 256 in the methodology of Figures 13A-M is not removed during the release.

Another method for making another embodiment of a reinforced microstructure 302 is illustrated in Figures 15A-G. In addition to being able to form a desired reinforcing structure, the methodology of Figures 15A-G further provides a desired manner for releasing the microstructure 302 at the end of processing by forming a plurality of at least generally laterally extending etch release channels in one or more of its sacrificial layers to facilitate the removal thereof when releasing the microstructure 302. Any of the layouts noted above for etch release rails may be used to form these etch release channels, but in the manner set forth in relation to Figures 15A-G.

Figure 15A illustrates a substrate 300 on which the microstructure 302 will be fabricated. Multiple layers are first sequentially deposited/formed over the substrate 300. A first sacrificial layer 304 is deposited over the substrate 300, and a first structural layer 308 is then deposited on the first sacrificial layer 304. The first support layer 308 is then patterned to define a plurality of lower reinforcement sections 312 of a reinforcing assembly 310 for the microstructure 302 as illustrated in Figure 15B. These lower reinforcement sections 312 are at least generally laterally extending. Adjacent lower reinforcement sections 312 are separated by a spacing 314 that is also thereby at least generally laterally extending as well. Generally, a relationship between the

distance between adjacent lower reinforcement sections 312 and the height or vertical extent of the lower reinforcement sections 312 is selected to allow a plurality of etch release channels to be defined in the spacings 314. In one embodiment: 1) the width or lateral extent of each of the spacings 314, or stated another way the distance between adjacent lower reinforcement sections 312 measured parallel with an upper surface of the substrate 300, is no more than about 1.5 μm; and 2) the height or vertical extend of each of the lower reinforcement sections 312 is at least about 1.5 μm. Stated another way, a ratio of the height of a given lower reinforcement section 312 to a width or lateral extent between this lower reinforcement section 312 and an adjacent lower reinforcement section 312 (i.e., one of the rail spacings 314) is at least about 1:1.

A second sacrificial layer 316 is deposited on the first structural layer 308 as illustrated in Figure 15C. The second sacrificial layer 316 extends within and occupies a portion of each of the spacings 314 that were previously formed from the first structural layer 308. However, the material that defines the second sacrificial layer 316 does not fill or occupy the entirety of the spacings 314 due to the relative close spacing between adjacent lower reinforcement sections 312 in relation to the height or vertical extent of the lower reinforcement sections 312. This may be characterized as "keyholing." In any case, the remaining voids in the lower portion of each of the spacings 314 define a plurality of at least generally laterally extending etch release channels 320.

The upper surface of the second sacrificial layer 316 may retain a wavy or uneven contour. The upper surface of the second sacrificial layer 316 may then be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the second sacrificial layer 316 and as illustrated in Figure 15C. In any case, the second sacrificial layer 316 is then patterned to define a plurality of interconnect apertures 324 as

illustrated in Figure 15D. These interconnect apertures 324 at a minimum allow for establishing a structural connection with the lower reinforcement sections 312, and may be in the form of at least generally laterally extending grooves or trenches (e.g. to define rails), or may be in the form of a plurality of separate and discrete holes that are disposed in spaced relation (e.g. to define a plurality of columns or posts). In any case, each interconnect aperture 324 is disposed directly above (e.g., vertically aligned) a corresponding lower reinforcement section(s) 312, although the lower reinforcement sections 312 will typically have a slightly larger width than their corresponding interconnect aperture(s) 324.

A second structural layer 328 is deposited on the second sacrificial layer 316 as illustrated in Figure 15E. The material that defines the second structural layer 328 is also deposited within and at least substantially fills the interconnect apertures 324 that were previously formed in the second sacrificial layer 316, and such may be characterized as being part of the second structural layer 328. This portion of the second structural layer 328 may be characterized as a plurality of upper reinforcement sections 332 that are the upper extreme of the reinforcing assembly 310 (Figure 15G) for the microstructure 302 that is being fabricated. Although Figure 15E shows an intersection between the lower extreme of each of the upper reinforcement sections 332 and the upper extreme of their corresponding lower reinforcement section 312, typically such an intersection will not exist and instead will at least appear to be a continuous structure.

The upper surface of the second structural layer 328 will typically have a wavy or uneven contour or at least a plurality of laterally disposed and preferably axially extending depressions. Generally, those portions of the second structural layer 328 that are disposed between adjacent upper reinforcement sections 332 will be recessed to a degree. Therefore, the upper surface of

the second structural layer 328 will typically be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the second structural layer 328 and as illustrated in Figure 15F. This completes the definition of the microstructure 302. It should be appreciated that the system that includes the microstructure 302 will likely include other components than those illustrated in Figures 15A-G and that may interface with the microstructure 302 in some manner (e.g., one or more actuators).

The microstructure 302 is now ready to be released. “Released” means to remove each sacrificial layer and thereby including the first sacrificial layer 304 and the second sacrificial layer 316. An etchant is used to provide the releasing function. Predefined flow paths for this etchant are defined in and extend through portions of the first sacrificial layer 304 and the second sacrificial layer 316 in the form of the above-noted etch release channels 320. The existence of the etch release channels 320 provides access to interiorly disposed locations within the sacrificial layers for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 302.

As opposed to other of the reinforced microstructures disclosed herein, the microstructure 302 is only a single structural layer (second structural layer 328) that is structurally reinforced by a plurality of “cantilevered” structures extending downwardly therefrom, namely the plurality of at least generally laterally extending lower reinforcement sections 312. Notwithstanding the characterization of the structures 312 and 332 as "reinforcement sections," it should be appreciated that the entire focus of the methodology of Figures 15A-G could in fact be to simply provide a plurality of at least generally laterally extending etch release conduits, to in turn provide a "rapid etch release function" for the microstructure 302. That is, it is not required that the structures 312 and 332 actually structurally reinforce the microstructure 302, although such is

preferably the case. Therefore, the structures 312 could also be characterized as etch release rails or the like.

The basic principle for forming etch release channels or conduits encompassed by the methodology represented in Figures 15A-G is that the deposition of a sacrificial material onto a layer having at least one and more typically a plurality slots having a height that is at least as great as the width produces a keyholing effect at the bottom of the slot, which in turn defines an etch release channel or conduit. The layer with the noted types of slots may exist at various levels within the microstructure being fabricated and yet still allow for the formation of etch release channels or conduits in this same general manner. Moreover, a layer with the noted types of slots does not need to be structurally interconnected with the uppermost structural layer of the microstructure being fabricated to allow for the formation of etch release channels or conduits in this same general manner. For instance, the layer with the noted types of slots instead could be anchored to the underlying substrate or another underlying structural layer. In fact, this layer with the noted types of slots need not remain in the final structure of the microstructure being fabricated at all, but instead may be removed during the release of the microstructure from the substrate.

Another method for making another embodiment of a reinforced microstructure 338 is illustrated in Figures 16A-C. Figure 16A illustrates a substrate 340 on which the microstructure 338 will be fabricated. A first sacrificial layer 340 is deposited over the substrate 336. The first sacrificial layer 340 may actually be a plurality of sacrificial layers that are deposited at different times in the process. In any case, the first sacrificial layer 340 is patterned to define a plurality of at least generally laterally extending apertures 344 as illustrated in Figure 16B. These apertures 344 do not extend down through the entire thickness of the first sacrificial layer 340 in

the illustrated embodiment, and may be made by a timed etch. These apertures 344 may also be made by first etching down to the substrate 336, and then backfilling with a sacrificial material in a subsequent deposition to provide apertures 344 of the desired depth.

The apertures 344 effectively function as a mold cavity and may be in any desired shape for the resulting reinforcing structure. For instance, the apertures 344 may be arranged to define a plurality of at least generally laterally extending ribs or rails (e.g., similar to the rails 118 of the mirror microstructure 106 of Figure 5; the rails 154 or 142 of the mirror microstructure 130 of Figure 7). Another option would be to arrange the apertures 344 to define a waffle pattern, honeycomb pattern, hexagonal pattern, or the like (e.g., a grid or network of reinforcing structures), such as defined by a plurality of intersecting rails that utilized by the mirror microstructure 166 of Figures 9A-B.

A first structural layer 348 is deposited on the first sacrificial layer 340 as illustrated in Figure 16C. The first structural layer 348 extends within and occupies at least substantially the entirety of each of the apertures 344 that were previously formed in the first sacrificial layer 340. Those portions of the first structural layer 348 that are disposed within the apertures 344 may be characterized as a reinforcement structures 352 that "cantilever" or extend downwardly from the first structural layer 348 at least generally toward the underlying substrate 336.

The upper surface of the first structural layer 348 may retain a wavy or uneven contour. The upper surface of the first structural layer 348 may then be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the first support layer 348. Thereafter, the first structural layer 348 is released by removing the first sacrificial layer 340. A plurality of small etch release holes (not shown) will extend through the entire vertical extent of the first structural layer 348 to allow for the removal of the first

sacrificial layer 340 that is disposed between the first structural layer 348 and the substrate 336. Therefore, the primary benefit of the design of the microstructure 338 is the structural reinforcement of the first structural layer 348 and the existence of a relatively large space between the lower extreme of the reinforcing assembly 352 and the substrate 336.

Another method for making a microstructure is illustrated in Figures 17A-G. This methodology may be utilized to make the mirror microstructure 106 of Figures 5-6, and the principles of this methodology may be utilized in/adapted for the manufacture of the mirror microstructure 30 of Figures 2-3, the mirror microstructure 58 of Figure 4, the mirror microstructure 130 of Figure 7, the mirror microstructure 384 of Figures 10A-C, and the mirror microstructure 384' of Figure 10D, as well as the variations therefore that are presented in Figures 11A-F. In addition to being able to form a desired reinforcing structure, the methodology of Figures 17A-G further provides a desired manner for releasing the microstructure at the end of processing by forming a plurality of at least generally laterally extending etch release conduits in one or more of its sacrificial layers to facilitate the removal thereof to provide the releasing function.

Multiple layers are first sequentially deposited/formed over an appropriate substrate 448 as illustrated in Figure 17A, including a first sacrificial layer 449, a first structural layer 450, and a second sacrificial layer 454. The second sacrificial layer 454 is then patterned to define a plurality of etch release conduit apertures 458 as illustrated in Figure 17B. These etch release conduit apertures 458 may be in the form of at least generally laterally extending grooves or trenches, and nonetheless are defined by a pair of at least generally vertically disposed and spaced sidewalls 462.

A third sacrificial layer 466 is then deposited on the second sacrificial layer 454 as illustrated in Figure 17C. The material that defines the third sacrificial layer 466 is also deposited within and at least substantially fills the etch release conduit apertures 458 that were previously formed in the second sacrificial layer 454, and such may be characterized as being part of the third sacrificial layer 466. Although Figure 17C shows an intersection between the third sacrificial layer 466 and the second sacrificial layer 454, typically such an intersection will not exist and instead will at least appear to be continuous. In any case, that portion of the third sacrificial layer 466 that is deposited alongside the sidewalls 462 of the etch release conduit apertures 458 will be of a lower density than other portions of the third sacrificial layer 466, as well as the second sacrificial layer 454 and first sacrificial layer 449 for that matter. These low density regions ultimately become a plurality of etch release channels as will be discussed in more detail below. It should be appreciated that the spacing between the sidewalls 462 of each aperture 458 may also be subject to the types of "keyholing" effects discussed above in relation to the methodology of Figures 15A-G. That is, in the event that the ratio of the height of the sidewalls 462 of a given etch release conduit aperture 458 to the spacing between these two sidewalls 462 is at least about 1:1, an etch release conduit or channel will also develop in the lower portion of this etch release conduit aperture 458 due to the "closing" off of the upper portion of this etch release conduit aperture 458 during the deposition of the third sacrificial layer 466.

The upper surface of the third sacrificial layer 466 may retain a wavy or uneven contour, as illustrated in Figure 17C. Generally, those portions of the third sacrificial layer 466 that are disposed over the etch release conduit apertures 458 may be disposed at a lower elevation than those portions of the third sacrificial layer 466 that are disposed between adjacent etch release

conduit apertures 458. In the event that this is the case and as illustrated in Figure 17D, the upper surface of the third sacrificial layer 466 may be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the stack as thus far defined. This planarization may totally eliminate the third sacrificial layer 466 except from within the etch release conduit apertures 458 as shown, or the third sacrificial layer 466 may remain as a continuous layer on the first sacrificial layer 454 (not shown, but in the manner depicted in Figure 19D discussed below).

Reinforcement structures may be incorporated into the microstructure using the method of Figures 17A-G. In this regard, the second sacrificial layer 454, as well as any overlying portion of the third sacrificial layer 466, may be patterned to define a plurality of interconnect apertures 470 as illustrated in Figure 17E. Notably, these interconnect apertures 470 are disposed between the etch release conduit apertures 458 that now have the material of the third sacrificial layer 466 therein. That is, preferably none of the interconnect apertures 470 extend downwardly through and/or intersect any of the etch release conduit apertures 458 that now include material from the third sacrificial layer 466. These interconnect apertures 470 allow for establishing a structural interconnection with the first structural layer 450, and may be in various forms. For instance, these interconnect apertures 470 may be in the form of at least generally laterally extending grooves or trenches (e.g., to define a plurality of rails or at least the upper portion thereof and of the type utilized by the microstructure 106 of Figure 5 and the microstructure 130 of Figure 7, as well as the variations therefore illustrated in Figures 11A-F), or may be in the form of a plurality of separate and discrete holes that are disposed in spaced relation (e.g., to define a plurality of posts or columns of the type utilized by the mirror microstructure 30 of Figures 2-3).

A second structural layer 474 is deposited on any exposed portions of the second sacrificial layer 454 and the third sacrificial layer 466, as illustrated in Figure 17F. The material that defines the second structural layer 474 is also deposited within and at least substantially fills the interconnect apertures 470 within the second sacrificial layer 454, and such may be characterized as being part of the second structural layer 474. This portion of the second structural layer 474 may be characterized as a plurality of reinforcement sections 478 for the microstructure 476 that is being fabricated. Although Figure 17F shows an intersection between the lower extreme of each of the reinforcement sections 478 and the upper extreme of first structural layer 450, typically such an intersection will not exist and instead will at least appear to be continuous.

The upper surface of the second structural layer 474 may retain have a wavy or uneven contour. Generally, those portions of the second structural layer 474 that are disposed over the reinforcement sections 478 may be recessed to a degree. Therefore, the upper surface of the second structural layer 474 may be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the second structural layer 474 and as illustrated in Figure 17F. This completes the definition of the microstructure 476. It should be appreciated that the system that includes the microstructure 476 will likely include other components than those illustrated in Figures 17A-G and that may interface with the microstructure 476 in some manner (e.g., one or more actuators). Moreover, it should be appreciated that the steps illustrated in Figures 17A-G may be repeated in an appropriate manner in order to define a microstructure of the type presented in Figures 4 and 7 (e.g., three or more spaced, but structurally interconnected, structural layers).

The microstructure 476 is now ready to be released. “Released” means to remove each of the sacrificial layers of the surface micromachined system and thereby including the first sacrificial layer 449, the second sacrificial layer 454, and the third sacrificial layer 466. An etchant is used to provide the releasing function. The manner in which the microstructure 476 was formed in accordance with the methodology of Figures 17A-G reduces the time required for the sacrificial layers 454 and 466 to be totally removed. Ultimately, a plurality of at least generally laterally extending etchant flow pipes, channels, or conduits are formed in the third sacrificial layer 466. Those portions of the third sacrificial layer 466 that are positioned alongside the sidewalls 462 of the etch release conduit apertures 458 that were formed in the second sacrificial layer 454 are less dense than the remainder of the third sacrificial layer 466. The etch rate will be greater in the low density regions of the third sacrificial layer 466 than throughout the remainder of the third sacrificial layer 466. This will effectively form an etch release pipe, channel or conduit in the third sacrificial layer 466 along each sidewall 462. The development of the etch release channels during the initial portion of the release etch provides access to radially inwardly disposed locations within the sacrificial layers for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 476.

The methodology represented by Figures 17A-G provides a number of advantages. One is that the first sacrificial layer 454 may be patterned to define any appropriate arrangement for the etch release conduit apertures 458 within/throughout a sacrificial layer(s) (and thereby an arrangement for the low density regions which will ultimately define the etch release conduits), including an arrangement where one or more of these etch release conduit apertures 458

intersect. That is, the formation of the etch release conduits is not adversely affected by having the low density regions intersect.

Figures 18A-B present one arrangement where the first sacrificial layer 454 has been patterned to define a network 482 or grid of one embodiment of intersecting/interconnected etch release conduit apertures 458. The network 482 of intersecting/interconnected etch release conduit apertures 458 increases the amount of the sacrificial layer that is initially exposed to the release etchant within radially inward locations, and thereby should reduce the total amount of time required to release the microstructure 476 that is being formed. The various etch release conduit apertures 458 may be routed to define a desired network 482 for distribution of the release etchant throughout the first sacrificial layer 454 to not only reduce this total etch release time, but to also allow for use of a desired reinforcing structure. In this regard, Figure 18B illustrates one embodiment that may be used for the reinforcement sections 478 in combination with the network 482 of Figure 18A. The reinforcement sections 478 of Figure 18B are in the form of a plurality of spaced posts or columns that structurally interconnect the first structural layer 450 and the second structural layer 474 of the microstructure 459 (e.g., for defining a microstructure of the type illustrated in Figure 2A).

Another advantage associated with the manner in which the etch release conduits are formed in the methodology of Figures 17A-G, is that these etch release conduits may be formed without requiring the use of any reinforcement structures. This is illustrated by the sequential view presented in Figures 19A-F. Multiple layers are sequentially deposited/formed over an appropriate substrate 488, including a first sacrificial layer 490 as illustrated in Figure 19A. The first sacrificial layer 490 is then patterned to define a plurality of etch release conduit apertures 492 as illustrated in Figure 19B. These etch release conduit apertures 492 may be of the type

used by the methodology of Figures 17A-G, and are defined by a pair of at least generally vertically disposed and spaced sidewalls 494.

A second sacrificial layer 496 is then deposited on the first sacrificial layer 490, as illustrated in Figure 19C. The material that defines the second sacrificial layer 496 is also deposited within and at least substantially fills the etch release conduit apertures 492 that were previously formed in the first sacrificial layer 490, and such may be characterized as being part of the second sacrificial layer 496. Although Figure 19C shows an intersection between the second sacrificial layer 496 and the third sacrificial layer 490, typically such an intersection will not exist and instead will at least appear to be continuous. In any case, that portion of the second sacrificial layer 496 that is deposited alongside the sidewalls 494 of the etch release conduit apertures 492 will be of a lower density than other portions of the second sacrificial layer 496, as well as the first sacrificial layer 490 for that matter.

The upper surface of the second sacrificial layer 496 may retain a wavy or uneven contour, as illustrated in Figure 19C. The upper surface of the second sacrificial layer 496 may be planarized in an appropriate manner, such as by chemical mechanical polishing, to yield a sufficiently flat upper surface for the stack as thus far defined and as illustrated in Figure 19D. This planarization may totally eliminate the second sacrificial layer 496 except from within the etch release conduit apertures 492 (not shown), or the second sacrificial layer 496 may remain as a continuous layer on the first sacrificial layer 490 as shown in Figure 19D.

A first structural layer 498 is then deposited on any exposed portions of the first sacrificial layer 490 and the second sacrificial layer 496, as illustrated in Figure 19E. This completes the definition of the microstructure 486. It should be appreciated that the system that includes the microstructure 486 will likely include other components than those illustrated in

Figures 19A-F and that may interface with the microstructure 486 in some manner (e.g., one or more actuators).

The microstructure 486 is now ready to be released. "Released" means to remove each of the sacrificial layers of the surface micromachined system and thereby including the first sacrificial layer 490 and the second sacrificial layer 496. An etchant is used to provide the releasing function. The manner in which the microstructure 486 was formed in accordance with the methodology of Figures 19A-F reduces the time required for the sacrificial layers 490 and 496 to be totally removed. Ultimately, a plurality of at least generally laterally extending etchant flow pipes, channels, or conduits are formed in the second sacrificial layer 496. Those portions of the second sacrificial layer 496 that are positioned alongside the sidewalls 494 of the etch release conduit apertures 492 that were formed in the first sacrificial layer 490 are less dense than the remainder of the second sacrificial layer 496. The etch rate will be greater in the low density regions of the second sacrificial layer 496 than throughout the remainder of the second sacrificial layer 496. This will effectively form an etch release pipe, channel or conduit in the second sacrificial layer 496 along each sidewall 494. The development of the etch release channels during the initial portion of the release etch provides access to radially inwardly disposed locations within the sacrificial layers for the etchant to complete the release before the etchant has any significant adverse effect on the microstructure 486.

Etch release channels that exist prior to the release of the microstructure 486 may also be formed by the "keyholing" concept discussed above in relation to Figures 15A-G. Generally, a relationship between the width of the etch release conduit apertures 492 and the height or vertical extent of these etch release conduit apertures 492 may be selected to allow a plurality of etch release channels to be defined in the lower portion of these apertures 492. When this

relationship is selected in the same general manner discussed above in relation to Figures 15A-G, the second sacrificial layer 496 will extend within and occupy only a portion of each of the apertures 492 that were previously formed from the first sacrificial layer 490. However, the material that defines the second sacrificial layer 496 will not fill or occupy the entirety of the apertures 492 due to the relative close spacing between the sidewalls 494 that define the etch release conduit apertures 492 in relation to the height or vertical extent of these apertures 492 (i.e., a void will remain in the lower portion of each aperture 492). This again may be characterized as "keyholing." In any case, the remaining voids in the lower portion of each of the etch release conduit apertures 492 will define a plurality of at least generally laterally extending etch release channels.

Another method for making a microstructure is illustrated by reference to Figures 20A-D. The fundamental principles of this methodology may be utilized to make the mirror microstructure 30 of Figure 2A, the mirror microstructure 58 of Figure 4, the mirror microstructure 106 of Figures 5-6, the mirror microstructure 130 of Figure 7, the mirror microstructure 384 of Figures 10A-C, the mirror microstructure 384' of Figure 10D, as well as the variations therefore that are presented in Figures 11A-F. In addition to accommodating the fabrication of at least certain types of reinforcing structures for the microstructure, the methodology embodied by Figures 20A-D further provides a desired manner for releasing the microstructure at the end of fabrication by forming a plurality of at least one at least generally laterally extending etch release conduit within one or more of its sacrificial layers to facilitate the removal of this sacrificial material during the release of the microstructure from the substrate.

Multiple layers of at least two different types of materials are sequentially deposited to define a stack 594 on a substrate 582 that is appropriate for surface micromachining. The

various deposition and patterning steps that may yield the configuration illustrated in Figure 20A have been sufficiently described in relation to other embodiments, and will not be repeated. The stack 594 includes a microstructure 592, which in the illustrated embodiment is in the form of a single structural layer 590 that is disposed in spaced relation to the substrate 582. Any configuration that is appropriate for the manner of defining etch release channels in the manner contemplated by Figures 20A-D may be utilized for the microstructure 592, including where the structural layer 590 is structurally reinforced in an appropriate manner. In any case, the stack 594 also includes an etch release conduit fill material 586 that is encased within a sacrificial material 584 both within the area occupied by the microstructure 592 and laterally beyond the microstructure 592 or "off to the side" of the microstructure 592. Generally, this etch release conduit fill material 586 is removed by a first etchant to form at least one laterally extending etch release conduit 602 at least somewhere underneath at least one structural layer of the microstructure 592. That is, the first etchant is more selective to the etch release conduit fill material 586 than the sacrificial material 584 in an amount such that it does not remove any significant portion of the sacrificial material 584. Thereafter, a second, different etchant (i.e., a release etchant) enters the etch release conduit(s) 602. This second, different etchant removes at least that portion of the sacrificial material 584 which is accessible through the etch release conduit(s) 602 to release the microstructure 592 from the substrate 582. That is, the second etchant is more selective to the sacrificial material 584 than the structural layer 590 in an amount such that it does not remove any significant portion of the structural layer 590.

The etch release conduit fill material 586 may be disposed at one or more levels relative to the substrate 582 within the microstructure 592. An at least generally vertically extending runner 588 of etch release conduit material 586 is disposed laterally beyond the area occupied by

the microstructure 592 (i.e., off to the side), and extends at least generally downwardly from an uppermost exterior surface 596 of the stack 594 toward the substrate 582 to the etch release conduit fill material 586 at one or more of the levels within the stack 594. Any appropriate number of runners 588 may be utilized, and each may be of any appropriate configuration.

The etch release conduit fill material 586 at any level within the stack 594 may occupy the entirety of this level under at least one structural layer of the microstructure 592. More typically, a patterning operation will have been done at a given level to define an appropriate layout of etch release rails from the etch release conduit fill material 586. Figure 20B illustrates one embodiment of a layout of etch release rails 598 of etch release conduit fill material 586 that are in the form of a grid or network. Other layouts for the etch release rails 598 may be utilized, including without limitation those discussed above. In the case of the embodiment of Figure 20B, sacrificial material 584 is also disposed at the same level within the stack 594 as the etch release rails 598 (i.e., in the space between adjacent etch release rails 598). Reinforcement structures 600 also may be disposed at the same level within the stack 594 as the etch release rails 598 in this same space as well if desired. These reinforcement structures 600 are separated from the etch release conduit fill material 586 by sacrificial material 584. That is, the etch release conduit fill material 584 is encased within sacrificial material 584.

Regardless of the layout of the etch release rails 598 of etch release conduit fill material 586, the microstructure 592 is released in the same general manner. Initially, the stack 594 is exposed to a first etchant that is selective to the etch release conduit fill material 586. In one embodiment, the etch release conduit fill material 586 is the same material that is used to form the various structural layers that define the microstructure 592. In this case, it is necessary for the various structural layers of the microstructure 592 to be isolated from the etch release conduit

fill material 586 by sacrificial material 584. There may be instances where a particular etchant may be sufficiently selective to the etch release conduit fill material 586 so as to not require this isolation of the structural material of the microstructure 592 from the etch release conduit fill material 586.

The first etchant removes the etch release conduit fill material 586 within the runner 588 to define an access 604, as well as any etch release rails 598 of etch release conduit fill material 586 connected therewith. This first etchant preferably does not remove any significant portion of any sacrificial material 584 that encases the etch release rails 598 and/or the runner(s) 588. The resulting void by this removal of material of the etch release rails 598 defines at least one etch release conduit 602 that is at least generally laterally extending and disposed under at least one structural layer of the microstructure 592 (Figure 20C). In the layout of etch release rails 598 illustrated in Figure 20B, there would be a grid or network of etch release conduits 602 within the sacrificial material 584 disposed under the area occupied by the structural layer 590.

There is a separate and distinct second etching operation in accordance with the methodology of Figures 20A-D. After the first etching operation has been executed to define at least one and more typically a plurality of etch release conduits 602, the stack 594 undergoes a second etching operation. The second etching operation uses a second etchant that is different from the first etchant, and that is selective to the sacrificial material 584. This second etchant flows down through the various accesses 604 that may be associated with the stack 594 and into any etch release conduit 602 fluidly interconnected therewith. The second etchant removes any sacrificial material 584 in contact therewith to release the microstructure 592 from the substrate 582 (Figure 20D). In the event that the etch release conduit fill material 586 is polysilicon, representative examples for the first etchant would be potassium hydroxide,

tetramethylammonium hydroxide, and xenon difluoride. Assuming that the sacrificial material 584 is doped or undoped silicone dioxide or silicone oxide, representative examples for the second etchant would be HF-based, including those identified above.

The foregoing description of the present invention has been presented for purposes of illustration and description. Furthermore, the description is not intended to limit the invention to the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings, and skill and knowledge of the relevant art, are within the scope of the present invention. The embodiments described hereinabove are further intended to explain best modes known of practicing the invention and to enable others skilled in the art to utilize the invention in such, or other embodiments and with various modifications required by the particular application(s) or use(s) of the present invention. It is intended that the appended claims be construed to include alternative embodiments to the extent permitted by the prior art.